A FINAL REPORT TO THE MINERALS MANAGEMENT SERVICE:

EVALUATION AND COMPARISON OF HURRICANE INDUCED DAMAGE TO OFFSHORE GOM PIPELINES FROM HURRICANE LILI

Prepared For
United States Department of the Interior
MINERALS MANAGEMENT SERVICE
Herndon, VA

August 31, 2005

Stress Engineering Services, Inc.
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Houston, Texas 77041

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Prepared For United States Department of the Interior MINERALS MANAGEMENT SERVICE Herndon, VA

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ABSTRACT

This report documents a study of hurricane-induced damage to offshore GOM pipelines due to Hurricane Lili. A detailed comparison of Lili with Hurricane Andrew shows both similarities and differences.

The largest number of damage events* was found to have occurred in 4-10-inch platform risers in water depths to 200 feet. Five location groupings experienced 63% of the damage, so we focused our study on small diameter riser damage. Failure Mode and Effects Analysis is used to pinpoint the principal failure modes and causes. Communications with various operator/owners provided us more details on the type of riser damage found.

Analysis methods were assembled to determine the recommended maximum clamp spacing for riser design based on both cyclic wave force fatigue as well as oscillatory Vortex Induced Vibration (VIV) considerations. Design recommendations are provided for riser/clamp spacing design, cathodic protection design/maintenance and bolted clamp design

* Our study was based on <u>number of failures</u> because our goal was to reduce failures. We did not normalize these results based on total miles of pipeline in the various size groups, and to do so might provide different insights..

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INTRODUCTION

Overview

Hurricane Andrew, in August of 1992, caused damage to many offshore pipelines in its path. The level of damage was such that the MMS contracted with Southwest Research Institute (SWRI) in San Antonio Texas to evaluate offshore pipeline damage. SES has reviewed and evaluated the SWRI final report (Reference 1) from a similarly named project regarding the "*Evaluation of Hurricane-Induced Damage to Offshore Pipelines*" based largely on damage due to Hurricane Andrew in 1992. We also reviewed and evaluated the MMS interim report: "*Hurricane Andrew's Impact on Natural Gas and Oil Facilities on the OCS*" (Reference 2).

The author appreciates the assistance of Mr. Michael Else, Ms. Elizabeth Komiskey and Mr. Steve Verret of the MMS in providing input data and advice.

Objectives

The objectives of this project were to:

1. Investigate pipeline failures resulting from Hurricane Lili, including flowlines, major trunk lines and platform risers from both fixed and floating production facilities.
2. Compare and contrast these failures with those reported from Hurricane Andrew in Reference 1.
3. Make specific recommendations for changes in design or operations guidelines that might prevent or mitigate such failures in the future.
4. Where possible, suggest cost-effective methods for making existing pipelines designed by older guidelines less likely to fail in the future.

Scope of Work

Our process started by first developing "typical" designs of the pipelines that showed the greatest number of failures in the categories. These categories would be chosen based on recent findings from Hurricane Lili, but take into account those cases covered in the Hurricane Andrew report. We would choose the pipe diameters to be typical of those that showed the greatest number of failures, and we would use water depths typical of those where the greatest number of failures occurred. Our thinking will be influenced by determining what kinds of damage would have the greatest environmental consequences.

Of course we performed the requisite hurricane damage data collection, evaluation and comparison task. Like SWRI, we also developed specific pipeline designs representative of those cases where pipelines were damaged. We started with the categories used by SWRI such as:

. • Mudslide damage
. • Riser damage
. • Platform damage causing riser/pipeline damage
. • Anchor damage
. • On-bottom stability damage
. • Other

Our approach has been: for each damage category we will first develop a detailed “typical” design based on permit or operator-supplied information on the pipelines that failed, including the most representative pipeline diameter(s) and water depth(s). Given the typical designs, we will then develop hypotheses of what types and magnitudes of hurricane-induced forces might result in damage to each pipeline damage category. Next, we reviewed current and past guidelines, codes and design practices (like References 3 and 4 and previous) to determine what changes might be made to preclude this type of failure. Finally we will attempt to suggest cost-effective “retrofit” changes that might be made to existing pipeline designs or operations to minimize future damage.

CONCLUSIONS

The following conclusions are offered:

1. Hurricane Andrew (1992) was a full category 4 throughout its path to landfall. Hurricane Lili (2002) was also a category 4 in the open Gulf, but diminished to category 2 at landfall. Consequently Andrew caused 490 segments of damage, where Lili caused 120 segments of damage.

2. The damage due to Lili affected all ages of pipelines equally, but 93% of the damage was in the small pipe sizes. Sixty-three percent of the failures occurred in the assets of only five pipeline location groupings. Seventy-nine percent of the pipe damage for those operators was found in risers. Hence we focused our investigation on understanding why the damage was focused on small-diameter risers for five operators.

3. Of the 78 incidents, data revealed that for 52 of the incidents the cause of damage was in the riser and for 11 of the incidents the cause of damage was in the clamps. As a result we focused on calculation procedures for determining maximum riser spacing for a 100-year return period hurricane.

4. It was not possible to learn much about detailed riser design for these mostly-older platforms. Discussions with owner/operators were made difficult because of asset sales and personnel change. It is fair to say that quality control practices have improved from that used when these risers were installed.

5. Riser failures do not cause major spills because the lines are shut in (but probably not de-pressured) during a storm event. It appears that the owners/operators are generally reactive unless forced otherwise. They shut in the system, and then turn it back on after the hurricane and see what repairs are needed. The marine growth that coats the risers makes effective diver or ROV inspection of the riser difficult.

6. Failure Modes and Effects Analysis (FMEA) was performed to show that the most critical failures were due to riser bending fatigue due to clamp spacing being too long, vibration of the riser due to oscillatory VIV and loose clamps, and pull-aways at the riser base due to unstable on-bottom pipeline segments joining the riser. The small diameter failure cause: Smaller risers can't span longer distances.

7. Design recommendations to avoid such damage as experienced are to recognize that small-diameter riser failure is a major cause of pipeline riser failure (for Lili and Andrew), and that prudent analysis of the riser and clamp design must be undertaken to result in a more robust riser system. Additionally, Maintenance must be performed throughout the riser, and cathodic protection design must be more intentional to avoid corrosion problems, and clamp must be engineered to ensure length of bolt in tension is adequate to ensure clamp relaxation. Finally the special case of clamped risers near the seafloor must be analyzed to provide maximum tolerance for on-bottom pipe movements in storms.

8. Remediation of existing riser systems is made difficult because marine growth covers any evidence of riser damage. Redundant diver-installed back-up clamps can be added in addition to the original clamp to provide a secondary defense to clamp failure. If the current riser spacing is larger than advised in this report, intermediate clamps could be added (near the splash zone where wave forces are greatest)

RECOMMENDATIONS

The following recommendations are offered:

1. The MMS pipe failure database has been a valuable source of information, and has been so for some years. An improvement would be to make revisions to the detailed questions asked of the operator/owners to elicit root causes. A simple "5-Why" analysis used by various companies would be useful in deciding changes to make. Thus more specific data would be submitted, leading to better solutions.

2. A simple check can be made by owner/operators to compare/contrast their as-built clamp spacings with the recommendations of this report. Perhaps additional clamps must be installed.

3. There is a difficult issue over reactive and proactive remediation of risers. Inspection of risers is made difficult by marine growth and by not knowing the extent of corrosion. If the MMS wishes to reduce the number of failures reported due to hurricanes the most prudent approach would be to discover weak or under-designed risers (including small-diameter) riser/clamp systems before the next hurricane hits, rather than counting the failures after the fact. The key is for operators/owners to find cost-effective ways to improve the reliability of all riser systems, including the small-diameter ones we studied.

4. Perhaps a simple in-situ riser integrity test method could be developed to discover and replace weak risers before the storms come.

5. These findings should be used as input to future recommended practices (RP) directed toward improving offshore pipeline reliability. If the pipeline reliability issue cannot be added to existing API or ASTM recommended practices, perhaps a new RP is needed. There is a similarity of pipeline

reliability with subsea system reliability (covered by API RP 17N being developed).

TECHNICAL APPROACH

Project Task List

Following are the tasks that were performed to achieve the stated objectives above:

1. Collected and evaluated pipeline damage data from the MMS database concerning Hurricane Lili. Also performed a simple literature search for public information relating to hurricane-induced pipeline damage. Requested additional hurricane damage related information from the MMS. Reviewed all available information.

2. Compared and contrasted statistical results from Hurricane Lili with those by SWRI on Hurricane Andrew. Developed typical damage categories from the data evaluation. Offered conclusions regarding the pipeline damage data.

3. Developed "typical" or pipeline designs representing the largest number of damages or the most significant oil or gas spill risk. Reviewed these typical designs with engineers from the operators who had damage, and refined the designs to make them most representative. Discussed the damages found with the same engineers to aid in developing hypotheses for the type of hurricane-induced forces that could have caused the damage.

4. Performed analyses on each type of damage category to determine the magnitude of hurricane-induced forces that were necessary to cause the damage. Refined hypotheses on hurricane-induced forces as necessary to result in a viable conclusion on the cause of failures.

5. Reviewed the applicable guidelines and codes, like ASME B31.4 and B.31.8, to determine what specific wordings could be changed to result in safer pipeline designs. Also compared key elements of the ASME codes with those from DnV and HSE, and included results of such comparisons.

6. Discussed results from 1 through 5 with the engineers mentioned previously and collected their feedback. Prepared a final report with the technical findings from this work.

DAMAGE COMPARISONS

Damage Comparisons – Lili vs. Andrew

Prior to making a comparison of these hurricanes we will review the Saffir-Simpson hurricane scale definitions found in Table 1:

Category	1	2	3	4	5
Winds	74-95 mph	96-110 mph	111-130 mph	131-155 mph	155 mph -above
Surge	4-5 ft	6-8 ft	9-12 ft	13-18 ft	18 ft - above

Table 1. The Saffir-Simpson Hurricane Scale.

In 2002, Hurricane Lili crossed the GOM heading towards the Louisiana coastline. In the process, the storm damaged approximately 120 pipelines. In the open gulf, Lili was a Category 4 hurricane, but just before it reached landfall it was downgraded to Category 2.

Figure 1 shows the Lili path to shore.

Figure 1. Path of Hurricane Lili.

Similarly, in 1992 Hurricane Andrew entered the GOM as a Category 4 Hurricane. Andrew damaged about 490 pipelines. Most of the pipelines were 20 years old and designed to previous codes. Please see Figure 2.

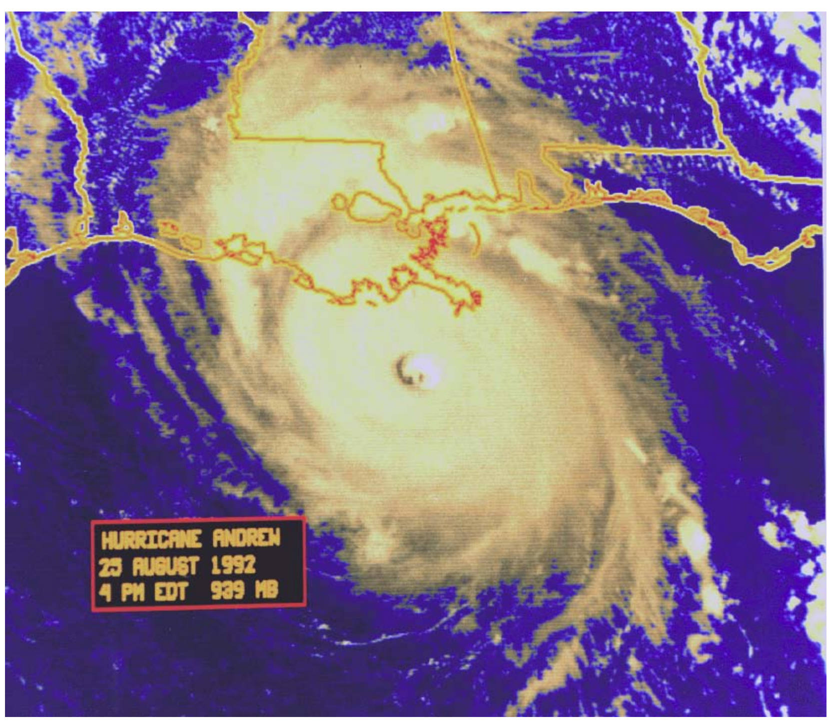


Figure 2. Hurricane Andrew.

A comparison of the major metrics of Hurricanes Andrew and Lili is shown in Table 2.

Hurricane Andrew - 1992	Hurricane Lili - 2002
Category 4 (full)	Category 4, then 2 near landfall
Wind Speed – 140 mph	Wind Speed – 145 mph
Gusts – 160 mph	Gusts – 160 mph
Storm Surges – 8 ft	Storm Surges – 8 to 10 ft

Table 2. Comparison of Andrew and Lili.

By referring to API 2A-WSD Platform Design Code, Table 2.3.4-1 shows high consequences to structures when:

- Wind speed = 92 mph
- Current Speed = 2.1 mph (21st Edition)
- Max Wave Heights = 30 to 68 ft.
- Wave Period = 13 seconds

Referring to Figure 3, “Percent of Failures by Age”, the figure shows that:

- The damage for Andrew occurred in pipelines that were greater than 12 years old (in 1992), and that pipelines in the 20-year age range suffered the greatest percentage of damage.
- For Lili the damage seemed to be uniformly spread among all ages of pipelines – the younger pipelines were not spared as in Andrew.

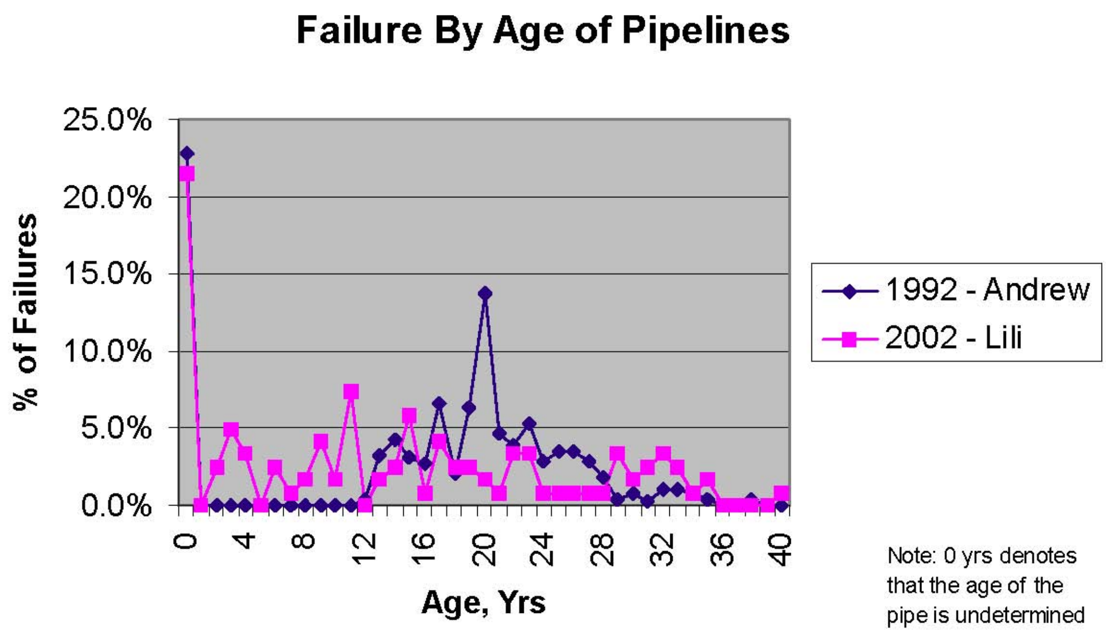


Figure 3. Percent of Failures by Age.

Turning now to failures per pipe size group, Figure 4 shows that the greatest percentage failures, 85%, occurred in the small pipe sizes: 2- to 6-inch. It is interesting that the % failures for size groups 2-6, 8-16, and 18-36 were the same for both Andrew and Lili. This figure suggests that the best area to focus on to reduce the number of failures would be to address issues for the 2-6 inch pipelines. Of course the greater volumes of oil lost could come from the 8-36 inch sizes.

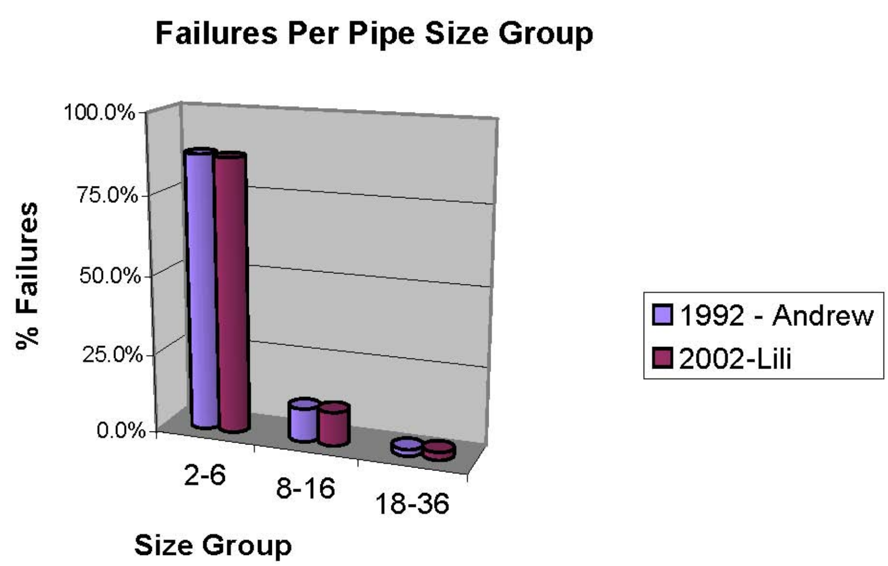


Figure 4. Percentage of Failure by Pipe Size.

By looking at the data in terms of where on the pipeline the failures were most numerous – failure location – Figure 5 shows that for both Andrew and Lili, most of the failures were in risers – 60 to 75 %, where most of the remainder occurred on bottom in the pipelines/flowlines. Only minor damages occurred at subsea tie-ins. Of course there are much fewer subsea tie-ins than pipelines/risers.

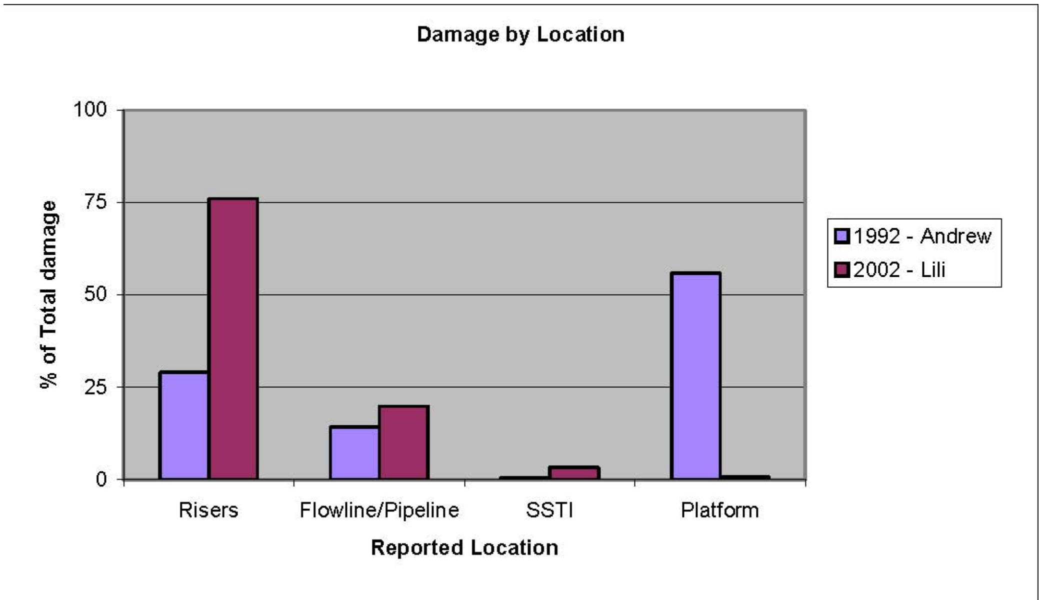


Figure 5. Location of Failures.

An interesting plot is to show the number of failures by pipeline location groupings. Such a plot is shown as Figure 6. What can be seen is that most operators experience only a few failures – for Andrew and Lili. But, particularly for Lili, the largest number of failures occurred in a few pipeline location groupings.

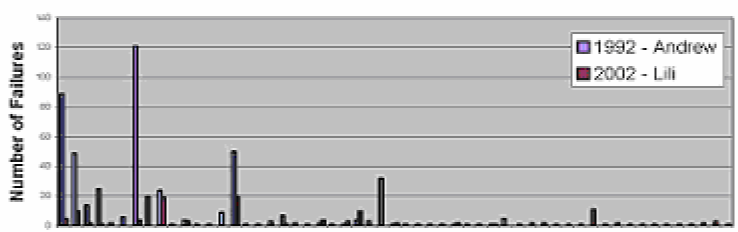


Figure 6. Location Groups

We will place a tighter focus on the data concerning pipeline location groups experiencing the most failures in order to get their valuable insights into why the pipelines/risers failed.

Damage for Hurricane Lili

Focusing on Hurricane Lili specifically, Figure 8 shows that the pipes sized between 2 and 6 inches accounted for 112 of the reported failures – 93 % of the total!

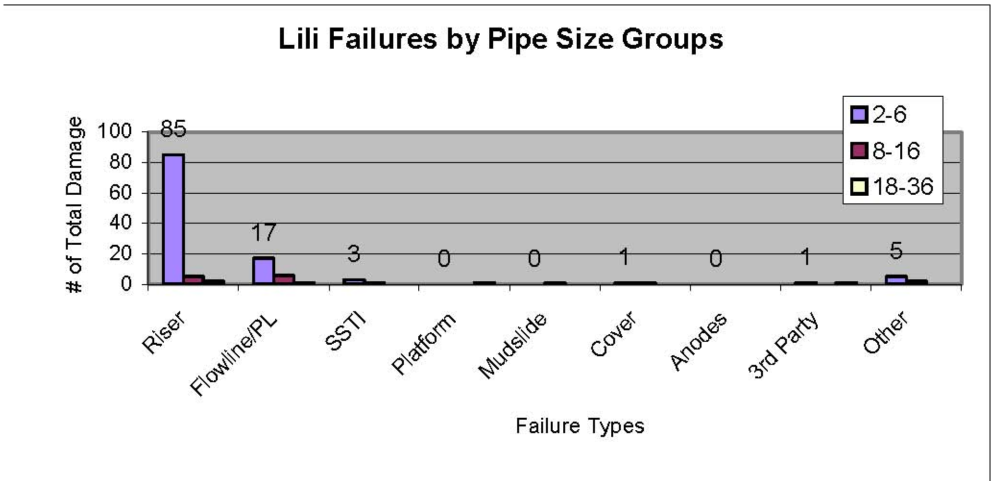


Figure 8. Failure by Pipe Size with Respect to Location.

By looking at Figure 8 we can derive the following pie chart, Figure 9, showing that only 5 location groups experienced the misfortune of dealing with 63 % of the 121 failures that occurred due to Lili.

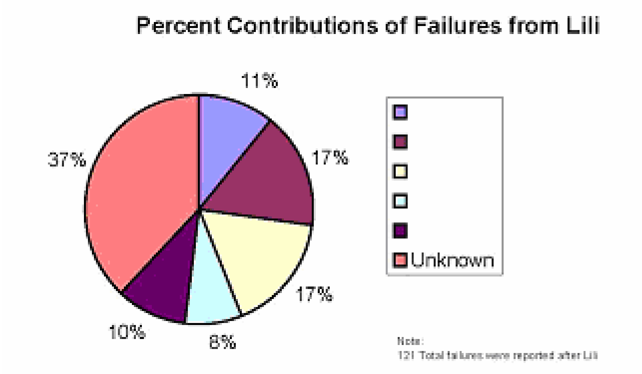


Figure 9. Percent Contributions to Failure by Location Groups.

Further in the evaluation, 79% of the failures for the 5 location groupings occurred in risers, as shown in Figure 10.

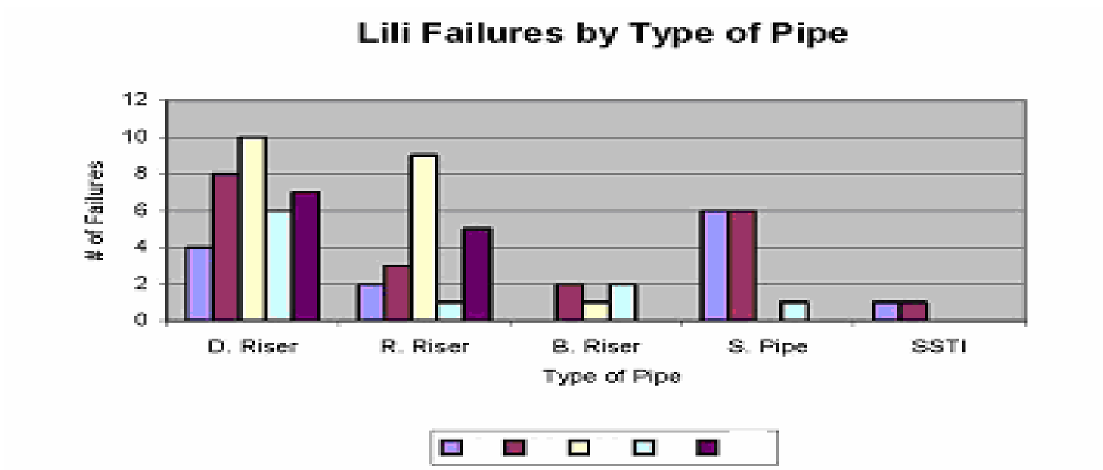


Figure 10. Failures by Type of Pipe.

Analyzing further, the risers where failures occurred were primarily in water depths less than 200 ft. Figure 11 depicts this information.

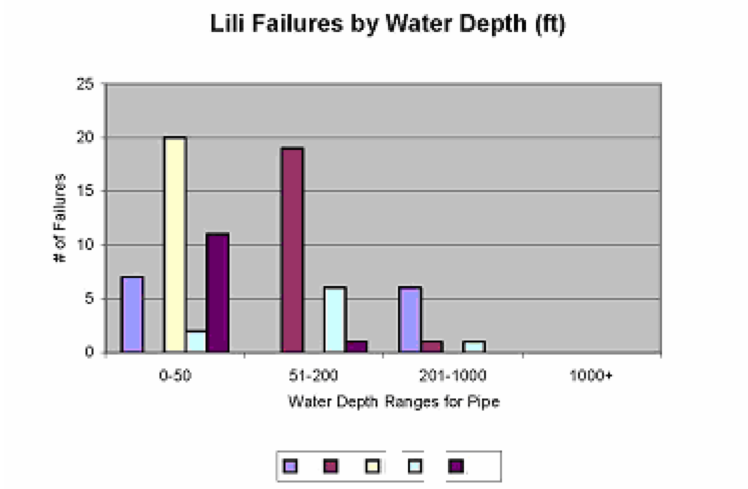


Figure 11. Water Depth Location of Failures.

Based on our review of the above Lili data we decided to concentrate our analysis focus on the small diameter riser failures, since resolving these issues could have a significant impact on reducing the number of future pipeline failures.

An additional finding - as we evaluated the data in the MMS database - is that the different operators describe the same kind of failures differently. For example a riser failure might be listed for a riser that fails due to a pipeline stability or mudflow problem at the base. Or the same riser failure would cover failure to a splashzone corrosion problem resulting in leakage. <u>It would be better in the future to address root causes of failures</u>.

The remaining failures we considered as “random” because it would be hard to collect enough valid <u>root cause</u> data to treat each failure condition effectively.

Types of Damage Experienced – Lili

Only six days after Tropical Storm Isidore entered the Gulf of Mexico with sustained winds reaching 56 knots, gusts up to 71 knots, and wave heights of 20 ft, Hurricane Lili traveled a similar path to reach the Louisiana coastline. On October 3rd, 2002 Hurricane Lili was centered in the North-central Gulf of Mexico. Lili reached estimated maximum wind speeds of 125 knots with gusts up to 130 knots as evident in Figure 12. Between Isidore and Lili, oil production in the gulf was temporarily curtailed due in part to the damages sustained by pipelines, risers, subsea tie-ins (SSTI), and platforms.

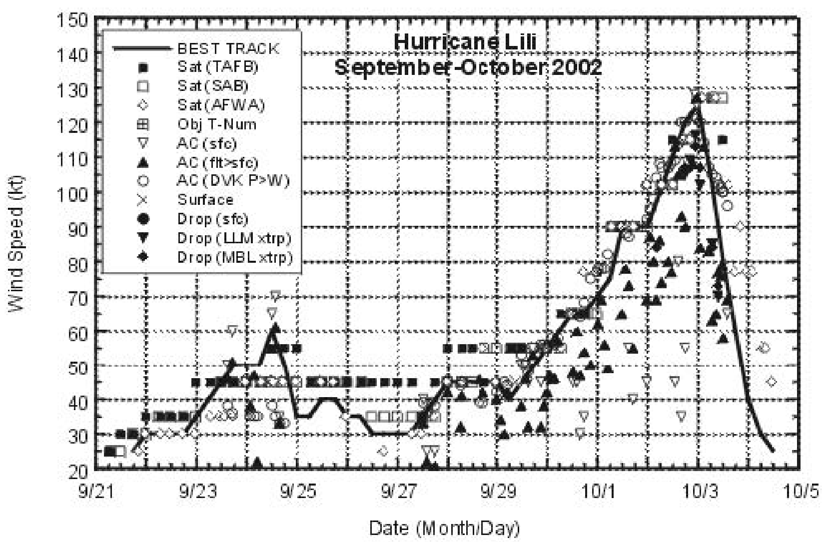


Figure 12. Lili 2002 Wind Data from NOAA website.

Figure 13 details the path of each storm and the locations of the damages accredited to the storms.

As evident in the figure, the highest concentration of damage occurs east of Lili's path but west of Isidore. The path of destruction is consistent with data collected on hurricanes. Generally, hurricanes generate more powerful winds, waves, and currents to the east of the eye of the storm.

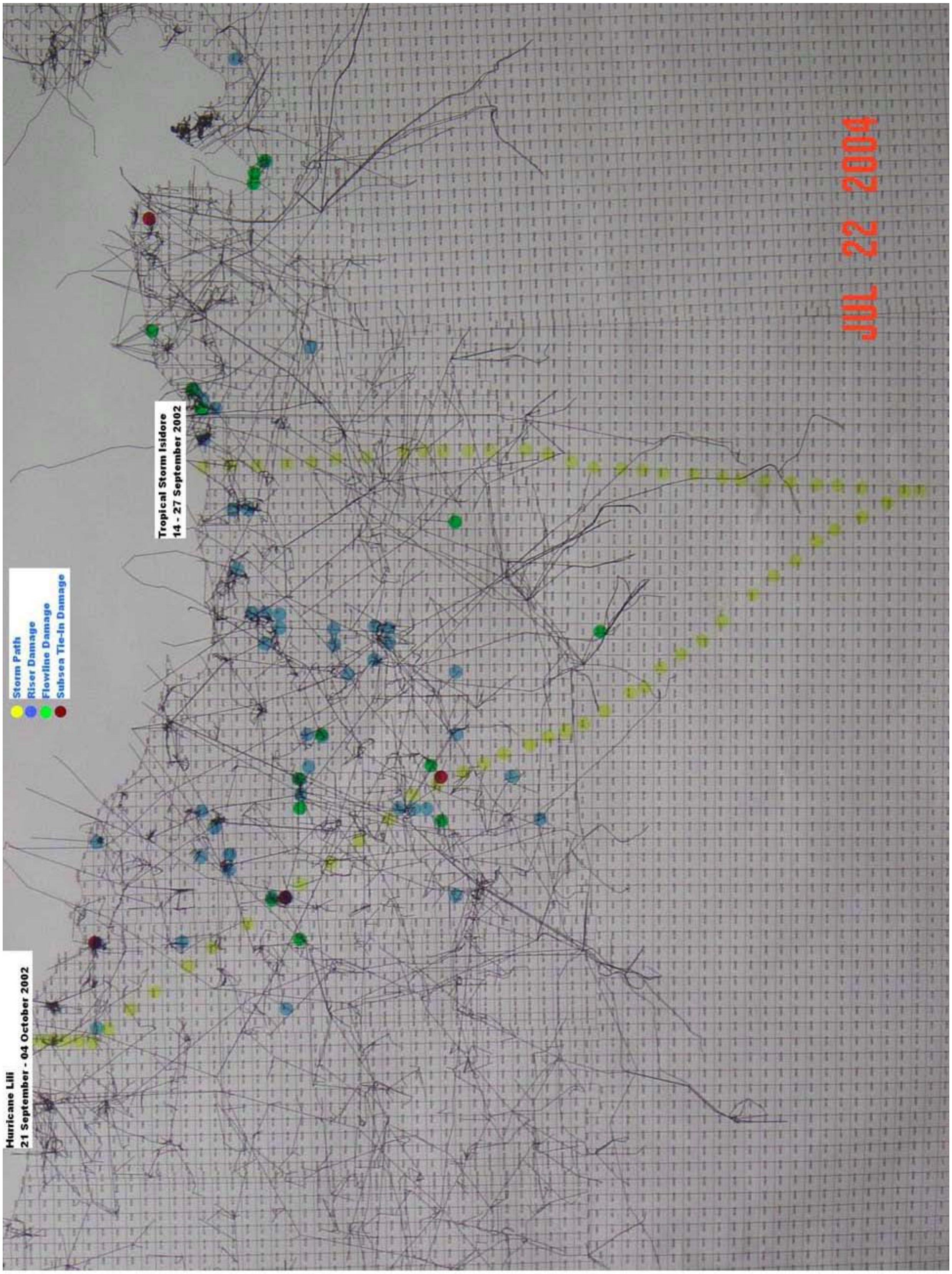


Figure 13. Storm Paths and Associated Damage.

Data was collated after the storms detailing the type of failures incurred. Figure 14 below shows the percent failure of the approximately120 pipelines that were damaged. As evident in the figure, over 75% of the damage reported occurred in risers.

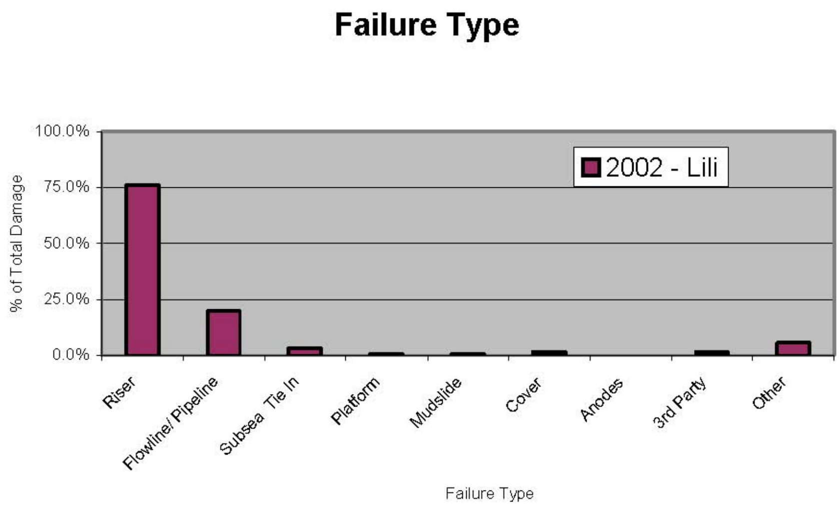


Figure 14. Types of Damage.

Figure 15 shows a further investigation of the types of pipes damaged cross-referenced with the location groupings involved as listed previously. The chart categorizes riser damage as departing, receiving, or both risers.

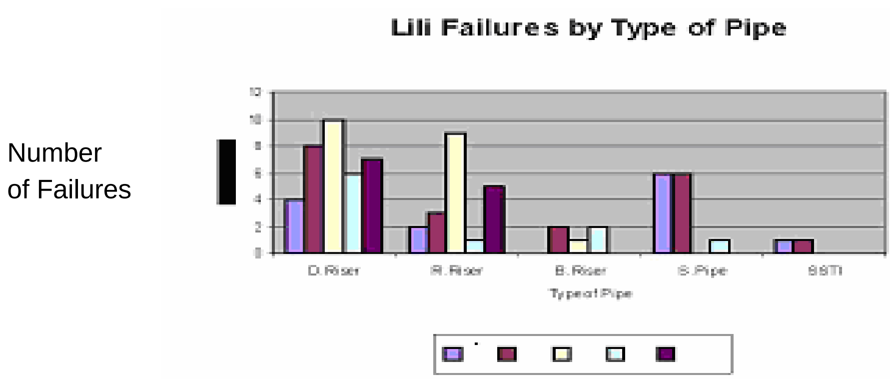


Figure 15. Pipe Type Failure

A further investigation into the root causes of damage to the risers yields the information provided in Table 3. The most significant number of damage occurred in the pipeline riser, followed by damage as a result of clamp failure.

Riser Damage Causes due to Lili - 2002	
Pipe Damage	52
Clamp Failure	11
Misc.	8
Missing Risers	4
I-tube Damage	1
Weld Damage	1
Platform Failure	1
.	
Total	78

Table 3. Breakdown of Riser Damage.

At the time that Hurricane Lili entered the Gulf of Mexico, there was approximately 30,000 miles of pipelines in the gulf. As stated previously, nearly 85% of the pipelines that were damaged were in the 2 – 6 inch pipe diameter range. However, a correlation between the number of miles of pipe failed and the total miles of pipe existing is detailed in Figure 16.

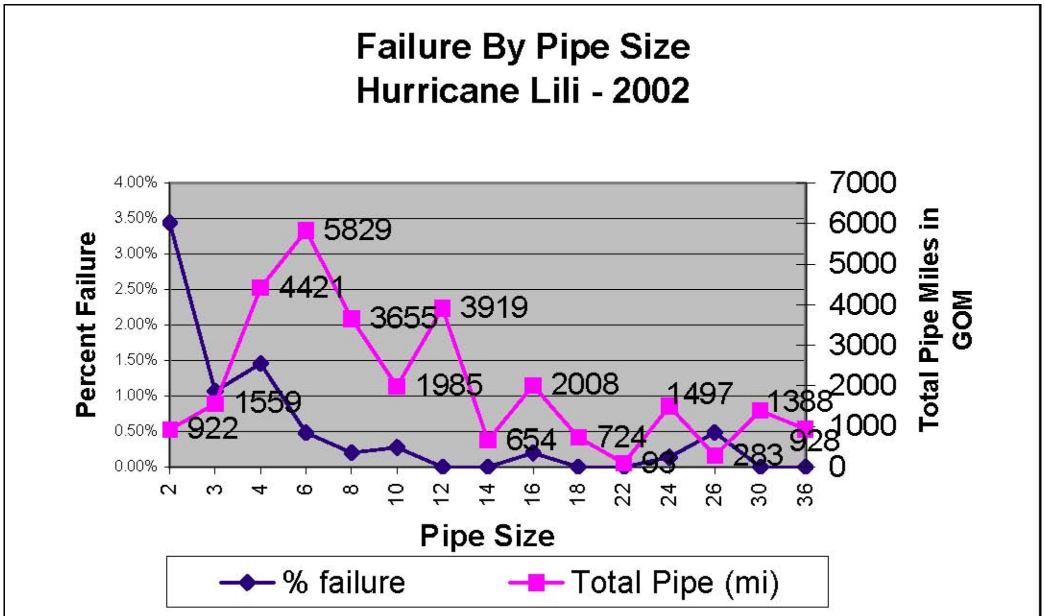


Figure 16. Miles of Pipe Failed vs. Total Pipe Miles.

The graph shows that pipelines in the 2 – 6 inch range again suffered the most damage with respect to the total number of miles existing pipeline. As an example 3.5% of the total pipeline miles of 2 inch outer diameter pipe failed due to Lili.

Although larger pipelines suffered far less damage, an investigation into the causes of the larger pipe damage is shown in Table 4.

Size (in)	Type	Contents	Age (yrs)	Blocks	Water Depth (ft)	Failure Mechanism
16	Departing Riser	Gas	15	EI 371-343	201-1000	Broken Clamp
16	Platform Piping	Gas	4	EI 346-327	201-1000	Line Parted
24	Subsea Pipe	Gas	7	GC 65 – SS 207	1000+	3rd Party, Concrete Damage
26	Departing Riser	Gas	33	EI 309	201-1000	Platform Failure
26	Departing Riser	Gas	23	SP 77-55	201-1000	(missing)

Table 4. Larger Diameter Pipeline Failures.

Large diameter pipe damage is important because it is likely a major trunkline to shore, and can represent a large loss of production, as contrasted with that for small-diameter lines.

Figure 17 depicts the failures in relation to the pipe contents with respect to the location groupings that experienced the most damage. No conclusions can be inferred by this graph except to say that there does not seem to be any discrimination by way of contents of the pipe.

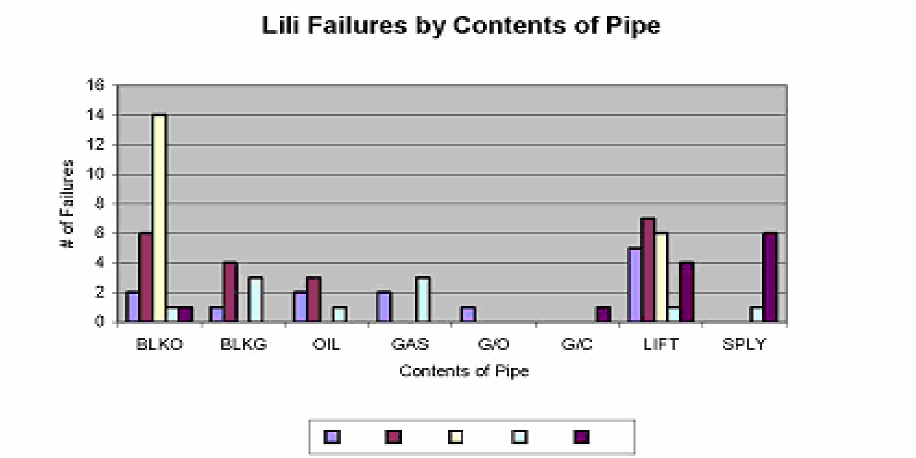


Figure 17. Failures by Pipe Contents.

Development of Design Recommendations

Based on the collated information from Hurricane Lili, certain design considerations can be inferred for further analysis. Therefore, as design guidelines, the following information could be used to evaluate current design considerations for environmental or storm conditions, clamp design, and mechanical designs of the pipe itself:

. • Pipe Outer Diameter (OD): 2 – 6 inches
. • Riser Design (departing or receiving)
. • Water Depth of less that 1000 ft
. • Pipeline in service (possible internal erosion or external corrosion) after a few years

. • Storm Tides greater than 12 ft

. • Wind gusts of at least 130 knots

. • Wave and Drag Loading

• Storm Tides greater that 12 ft

Assessment of Riser Damage Characteristics

The focus of this report has been to investigate small-diameter riser damage causes, since the Lili pipeline damage statistics showed such damage to be of greatest interest. Historically such small-diameter risers are not subjected to as detailed an evaluation as large-diameter risers. Often the risers are installed after the platform is set in place, using divers to assist the risers into the preset clamps and to fasten them. The clamped platform risers we have studied are represented as in Figure 18.

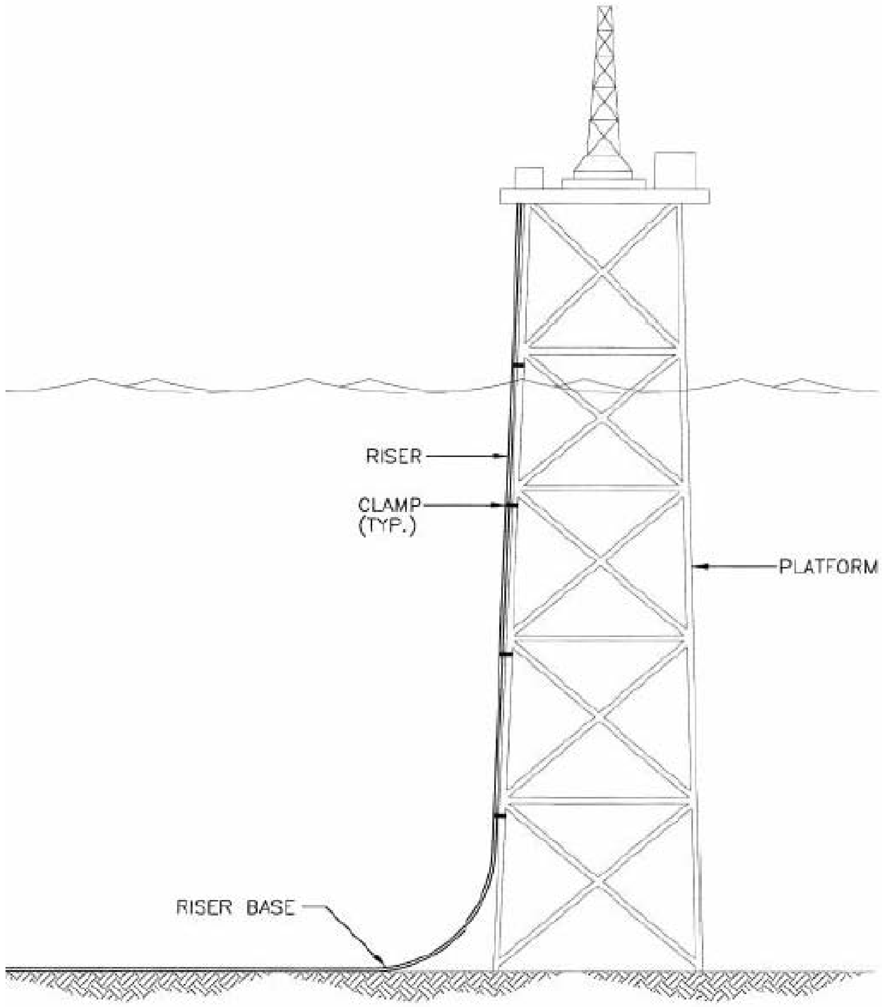


Figure 18. Clamped Riser Configuration Studies in This Project

Even though these risers are small-diameter, wave-induced forces during hurricanes, oscillate these small diameter risers, and they experience high bending stresses midway between clamps, as well as oscillatory vortex-induced vibrations, found greatest in the out-of-plane direction (orthogonal to the wave motion).

Codes for Riser/Clamp Design

The traditional platform design code used for the GOM is API RP 2A-WSD. In 1.3.3 the code says that it is the responsibility of the platform owner to select a design sea state. For pipelines ASTM B31.4 and B 3.8 are used. In checking older pipelines, we refer to API RP 1111, which did not exist when most of the platforms were constructed.

ASSESSMENT OF SMALL-DIAMETER RISER DAMAGE FOR LILI

Major Riser Damage Risks – Lili

It is clear from the above data that small-diameter riser failures are of great concern. The problem is that we could not obtain sufficient and consistent detailed data either from the MMS Database or from the riser owner/operators we talked to. As a consequence we decided to perform a Failure Modes and Effects Analysis (FMEA) to organize the potential root cause failure mechanisms that were involved in the riser system failures due to Lili.

FMEA Methodology

We conducted a "system" FMEA for the complete riser and clamp system. We use the word riser system to denote the vertical riser plus the clamps and bolting system. That is, we have determined failure modes for each component and the vertical location of the riser system. Each Failure Mode has a corresponding Severity Index. And, each Cause has Occurrence and Detection Indices. In our case, we determined that the Detection Index was not useful because the damage occurred once the platform was evacuated, and hence there was little difference in the ability to detect the failure. Traditionally the Risk Priority Number (RPN) is the product of these three indices and gives an overall relative level of risk corresponding to each Failure Mode and respective Cause. We are using only the Severity and the Occurrence Indices.

FMEA Index Meanings

Provided are tables depicting the ranges (in terms of numeric scale, corresponding to a description) of the Severity and Occurrence Indices. A few comments are provided within the Severity Index and Occurrence Index tables to indicate our assumptions on the "typical" severity of Failure Modes. The higher the Severity Index, the worse the problem is. The Occurrence Index is a probability that a given Cause will occur. Thus, the higher the Occurrence Index, the more probable the specific Cause-based event. And lastly, the Detection Index, not used in this analysis, is the measure of how likely you are to know about a potential Cause prior to its happening. Since the damage occurs when the platform has been evacuated, the likelihood of detection during the storm event is the same once personnel return to the platform. If the Detection Index is low, there is an excellent chance of knowing about a specific Cause-based event before it can occur. If the Detection Index is high, you have very little possibility of knowing about the Cause-based event before its occurrence. That is, the 'surprise' factor will be greater.

One word of instruction is that the FMEA results are most helpful when the indices are applied through the full range of 1 to 10. This causes the greatest range of RPNs that distinguish the failure modes best.

The table of indices that we used for Severity and Occurrence are shown as Table 5 and Table 6 below.

FMEA Criticality Analysis Index Codes

Severity Index

Severity	Criteria	Ranking
Hazardous	Hazardous effect. Safety related. Sudden failure. Noncompliance with government regulations.	10
Serious	Potential hazardous effect. Able to stop product/service without mishap. Safety related. Time-dependent failure. Disruption to subsequent process operations. Compliance with government regulation is in jeopardy.	9
Extreme	Customer very dissatisfied. Extreme effect on process/service; equipment damaged. Product/service incomplete but safe.	8
Major	Customer dissatisfied. Major effect on service; rework on service necessary. Product/service performance severely affected but functionable and safe.	7
Significant	Customer experiences discomfort. Product/process performance degraded, but operable and safe.	6
Moderate	Customer experiences some dissatisfaction. Moderate effect on product or service performance.	5
Minor	Customer experiences minor nuisance. Minor effect on product or service performance. Fault does not require attention.	4
Slight	Customer slightly annoyed. Slight effect on product or service performance.	3
Very slight	Customer more likely will not notice the failure. Very slight effect on product / process performance.	2
No	No discernible effect on product or subsequent processes.	1

Table 5. Severity Index Values for Use in the FMEA.

FMEA Criticality Analysis Index Codes		
Occurrence Index		
Occurrence	**Criteria**	**Ranking**
Almost Certain	Failure almost certain.	10
Very High	Very high number of failures likely.	9
High	High number of failures likely.	8
Moderately High	Frequent high number of failures likely.	7
Medium	Moderate number of failures likely.	6
Occasional	Occasional number of failures likely.	5
Slight	Few failures likely.	4
Very slight	Very few failures likely.	3
Rare	Rare number of failures likely.	2
Unlikely	Failure unlikely. History shows no failures.	1

Table 6. Occurrence Index Values for Use in the FMEA.

Results of a Standard FMEA Risk Analysis

Now that the FMEA methodology has been explained, we provide a table of the highest ranked failure modes in our analysis in Appendix A. The highest-ranked causes (RPN = 90) are as follows:

1. Riser wet buckle/rupture due to riser clamp failure (loss of clamp) causing higher bending stresses or increasing fatigue damage due to the longer resulting span between clamps.
2. Riser wet buckle/rupture due to vortex-induced vibration of the riser pipe span, occurring due to oscillatory water velocities associated with hurricane wave motions.
3. Riser wet buckle/rupture due to mudflows or mud slides pulling away flowlines attached to the riser at the lowest clamp at the riser base.

For RPNs of 70 to 80 the failure modes and causes are:

1. Riser wet buckle/rupture due to direct vessel collision with the riser near the splash zone.
2. Wet or dry buckle due to clamps opening – caused by wave force vibrations loosening bolts/nuts.
3. Wet or dry buckle due to clamps opening – caused by corrosion of the clamps or bolts/nuts.

Conclusions from FMEA Risk Analysis

It is clear from our evaluations that the use of improved design practices could minimize most of these failure modes. Granted that stray vessel collision during a hurricane is difficult/expensive to design for. For the rest, the following design elements are appropriate for small-diameter risers:

1. Treat small-risers as a critical design component, and determine the safe clamp spacing to minimize damage due to hurricane wave forces and oscillatory VIV in hurricane waves.
2. Improve cathodic protection design and maintenance for the risers, clamps and bolting in order to minimize corrosion damage. Adequate maintenance is the real issue, according to the MMS. Make sure that “Splashtron” or equivalent is used in the splash zone to minimize riser corrosion failure.
3. Improve the clamp design to ensure that the clamps are “engineered” - spring-loaded against the riser, preventing loose clamp vibration that would cause the bolting to loosen and resulting in opening of the clamp.

Results From Communications With Various Operators/Owners

With permission from the MMS, we contacted some owners/operators to obtain their views concerning riser damage. These contacts were made by both e-mail and telephone.

The text of the message sent was:

Dear Pipeline Operator/Owner,

I am writing you because you are my best contact in your company. You may decide to give this message a forward pass to a more appropriate person.

Stress Engineering Services is working on a project for the MMS to determine why pipelines were damaged during Hurricane Lili, and recommend improvements to mitigate damage in the future.

Further, of 121 pipeline failures for five groupings, 88% were riser failures. The risers were for the most smart small-diameter - 2-inch to 6-inch.

We have looked at riser and clamp designs, but it is impossible to recover much design data (like clamp spacing) from these riser systems.

We are hoping that your company would volunteer to provide your advice on why *you think your risers failed, and what you think could be done to avoid or minimize future failures.*

I have received permission from the MMS to make this request, but I know of no requirements for you to assist me.

I feel that you could have some very valuable advice to offer us to improve pipeline safety. So far we have looked at (1) the design clamp spacing on risers, (2) clamp design itself and (3) riser/clamp installation issues.

<u>Please call me at 281-955-2900 for more information.</u>

Thank you,

Contact Results

Those contacted did their best to help us, but often we could not communicate with the person most knowledgeable about the damages incurred. Personnel turnover and company ownership changes were the problems encountered.

Nevertheless we received the following general feedback:

1. Riser failure was likely caused by:
    a. Insufficient clamps used.
    b. Clamps at the waterline not being maintained, causing the clamps or bolts to corrode and become unclamped.
    c. The clamp design was not followed as intended and was not built as robustly as needed to resist the hurricane wave forces.

2. Consider the following:

    a. The condition of the risers, standoffs, and clamps <u>at and above</u> the waterline were in poor condition. From the wave zone up to the incoming pig traps, corrosion and blistered steel on the pipe and underneath the Splashtron coating was a factor. The larger waves generated by a hurricane takes out the weaker risers while the stronger risers survive to fail another day.

b. Marine growth on risers makes them heavier and provides a higher amount of surface area (to increase drag forces). Again, waves generated by hurricanes and large storms push against these “fat” risers until eventually they fail.

c. I think spacing of standoffs and clamps has been too wide in the past.

d. Finally, there is no such place (seafloor location) as a “self burial” area that adequately covers a newly laid pipe with enough good soil to protect it from anchor drags, shrimp nets, and undertows. Several of our newly laid lines were pushed (by soil forces) far off the surveyed route (because they were light and unstable) and pulled the risers away from the platform, taking lower clamp(s) with them.

Follow-Up Questions and Responses

There was an opportunity to follow up on the responses given to my e-mailed list of questions sent to the owner/operators who have riser failure experience. One response received was particularly useful:

Q: Would an inspection at and below the waterline turn up risers that need repair? Is there a way to avoid this failure mode?

A: Not necessarily. A pipe that “looks” to be in good / bad condition may not actually be in good / bad condition. It could just be “ugly” from existing in a harsh saltwater environment. The only way I can be sure mechanical integrity exists and a line will hold its MAOP is to hydro or pressure test it. The clamps/standoffs usually require a diver or ROV to inspect it if below the water line. The cost to repair a riser after a storm or change it out following an inspection is the same so there is probably little incentive to change out all risers that “might” be bad. I have seen NDT reports indicating adequate wall thickness for service on pressured lines and 2 weeks later a failure occurred.

Q: Is it worthwhile to scrape these risers with marine growth?

A: Can they be scraped without damaging the protective coatings?

Q: Does this mean that the primary failure was on-bottom stability, and that the riser became the break-away mechanism?

A: Yes, in some cases that is what appears to have happened. The riser failed from the pull and strain of lines being pushed along the bottom by undertows and currents and were moved up to 3000’ off of their original lay route. These were all recently laid lines in “self burial” areas.

Q: What role does the clamp design or the bolting or the diver bolting the clamps play in this? Any comment?

A: The high repetition of unidirectional waves when a hurricane approaches plays a part in the metal fatigue that is experienced by clamps and standoffs trying to hold a pipe buffeted by the “surf”. When one clamp fails (from rust, boat collision, improper installation, etc.), the load it was bearing now has to be divided among the remaining clamps. They in turn start to feel the strain, fail, and so on until the entire riser is free and fails unless the storm ceases.

Q: What does your company plan to do if you have experienced leaks?

A: We have not experienced “leaks”. We are active in preventive maintenance <u>for above waterline equipment</u>. We aim to address riser & clamp condition above the water line when observed to be less than ideal (missing bolts, cracked welds, etc.). Having them in the best condition they can be prior to a storm should help. On new installations a clamp close to the mudline is being included where possible. We are discussing the self-burial aspect of pipelines.

DESIGN RECOMMENDATIONS FOR SMALL-DIAMETER RISER SYSTEMS

Overview

Defining the riser system to consist of:

1. Standoffs from the platform leg
2. Riser clamps, rubber padding (if any) and bolts/nuts
3. The splash zone section of the riser
4. The touchdown point of the riser on the seafloor connecting to the on-bottom pipeline

It is prudent to follow the following general guidelines (based on FMEA results):

1. Treat small-risers as a critical design component, and determine the safe clamp spacing to minimize damage due to hurricane wave forces and oscillatory VIV in hurricane waves.
2. Improve maintenance for the risers, standoffs, clamps and bolting in order to minimize corrosion damage. Make sure that "Splashtron" or equivalent is properly applied in the splash zone to minimize riser corrosion failure.
3. Improve the clamp design to ensure that the clamps are'engineered' - spring-loaded against the riser, preventing loose clamp vibration that would cause the bolting to loosen and resulting in opening of the clamp.

We will address these three areas more fully in the following sections.

Summary

Maximum clamp spacings were calculated for a vertical riser suspended from a fixed platform in 200 ft of water. Details of the calculation methods are shown in Appendix C. A range of pipe diameters, 2 to 10 inches, was considered for the riser. The criterion for determining the maximum clamp spacing was based on the storm wave fatigue accumulation during a severe hurricane event. Vortex-induced vibrations (VIV) were also considered in this analysis by determining what maximum clamp spacing would limit the VIV vibrations to the fundamental frequency only.

Procedure

Twelve AISC standard weight and extra strong riser pipes were considered with nominal diameters ranging from 2” to 10”. Each riser pipe was formed from AISI 1040 steel with a Young’s modulus of 29 Msi, a yield strength of 42 ksi, and an ultimate strength of 76 ksi.

The severe storm event used in this analysis was a 100-year wave hurricane, characterized by a wave height of 65.5 ft and a wave period of 12.6 seconds. The duration of this storm at the location of the riser was assumed to be 3 hours. A drag coefficient value of 1.2 was prescribed for the riser. This value is typical for risers during severe storm events like the 100-year wave hurricane. The wave profile, particle velocities, and total pressures for the 100-year wave hurricane were calculated according to Stokes fifth-order wave theory.

The MMS suggests using a simpler method of using a fluid velocity of 33 ft/sec in Morrison’s equation to determine the forces and clamp spacing. We have made this calculation and show results for this as well.

For the Stress (not MMS) method, we have used an iterative solution method to calculate the maximum clamp spacing for each riser pipe. This method included the following steps:

1. The section of the riser located between the uppermost clamp (at the mean water line) and the next lower clamp (below the mean water line) is represented as a simply-supported pipe (conservative). At first, the location of this next lower clamp was unknown; therefore, an initial guess at its location had to be specified. Wave loads determined from Stokes

fifth-order theory were imposed on this section of the pipe, and the resulting bending stresses were calculated. See MMS recommendation (underlined) on previous page.

2. Maximum bending stresses were used to calculate fatigue lives for both welded and unwelded regions of the riser pipe. Fatigue lives for the unwelded base metal and connectors were calculated using the 1984 DOE B curve with a stress concentration factor of 3.0. Fatigue lives for the welded regions were calculated using the 1984 DOE W curve. No stress concentration factor was applied to the welded regions. Finally, a factor of safety of 2 was applied to all calculated fatigue lives.
3. If the amount of fatigue that accumulated during a 3-hour event had exceeded 10% of the overall fatigue life of the riser, then the initial guess was incorrect. The initial location of the next lower clamp was too far from the uppermost clamp, and a new iteration of the solution method would then be required. Iterations continued until the location the next lower clamp resulted in a single event fatigue life that was close (but not equal to) 10% of the overall fatigue life of the riser. Multiple iterations were often necessary to achieve a converged solution.

Calculation Results

Table 7 shows the results of our calculation of the maximum clamp spacing recommended for traditional riser clamps in water depths to 200 feet. In the table, two columns of clamp spacing are provided, based on the conditions shown. The MMS recommendation (see tabulated results) will result in a table that is depth independent.

Fatigue: One set of results is for the direct drag forces occurring on the riser due to hurricane waves. This result is based on the riser losing less than 10% of its fatigue life in one 3-hour hurricane passing the platform. The calculations are purposefully conservative, and assure long life for the riser (provided corrosion does not become a factor), because the riser could remain undamaged for 10 hurricanes passing through in the lifetime. This means that the allowable stresses in the riser are generally small, compared with yield stress in order to ensure a long fatigue life.

VIV: Although detailed VIV calculations were not made, we calculated a maximum clamp spacing based on constraining the riser span to vibrate only at its fundamental modal frequency (FMF). This means that multimode VIV is excluded, and that such vibrations would be a strong design factor – provided that clamps are tight and intact. With vibration only in the fundamental mode the frequency of vibration is reduced, and the number of cycles of vibration during a hurricane is thus reduced, increasing overall fatigue life. The periodic nature of the vibrations, as contrasted to VIV due to loop currents, makes VIV in this case less of a problem.

Maximum Clamp Spacing

AISI 1040 HR: E = 29 Msi; Yield Strength = 42 ksi; Ultimate Strength = 76 ksi
100-Year Hurricane: Wave Height = 65.5 ft; Wave Period = 12.6 s; Umax = 17.38 ft/s

Standard Weight

Nominal Diameter (in.)	Max. Clamp Spacing based on Wave Fatigue (ft)	Revised Max. Clamp Spacing if FMF = SMF (ft)	Max. Clamp Spacing based on 33 fps Slab Current (ft) MMS
2	6	3.9	7.8
3	10	5.8	11.3
4	12	7.5	13.6
6	16	11.1	18.2
8	21	14.5	22.4
10	25	18.1	26.8

Extra Strong

Nominal Diameter (in.)	Max. Clamp Spacing based on Wave Fatigue (ft)	Revised Max. Clamp Spacing if FMF = SMF (ft)	Max. Clamp Spacing based on 33 fps Slab Current (ft) MMS
2	7	3.9	8.9
3	11	5.7	12.8
4	14	7.4	15.7
6	20	11.0	21.8
8	25	14.3	27.1
10	29	18.0	30.8

Table 7. Recommended Maximum Spacings for Wave Fatigue and VIV.

A plot of these results is shown in Figure 19, and more details of the calculation results leading to Table 7 are included in Appendix D.

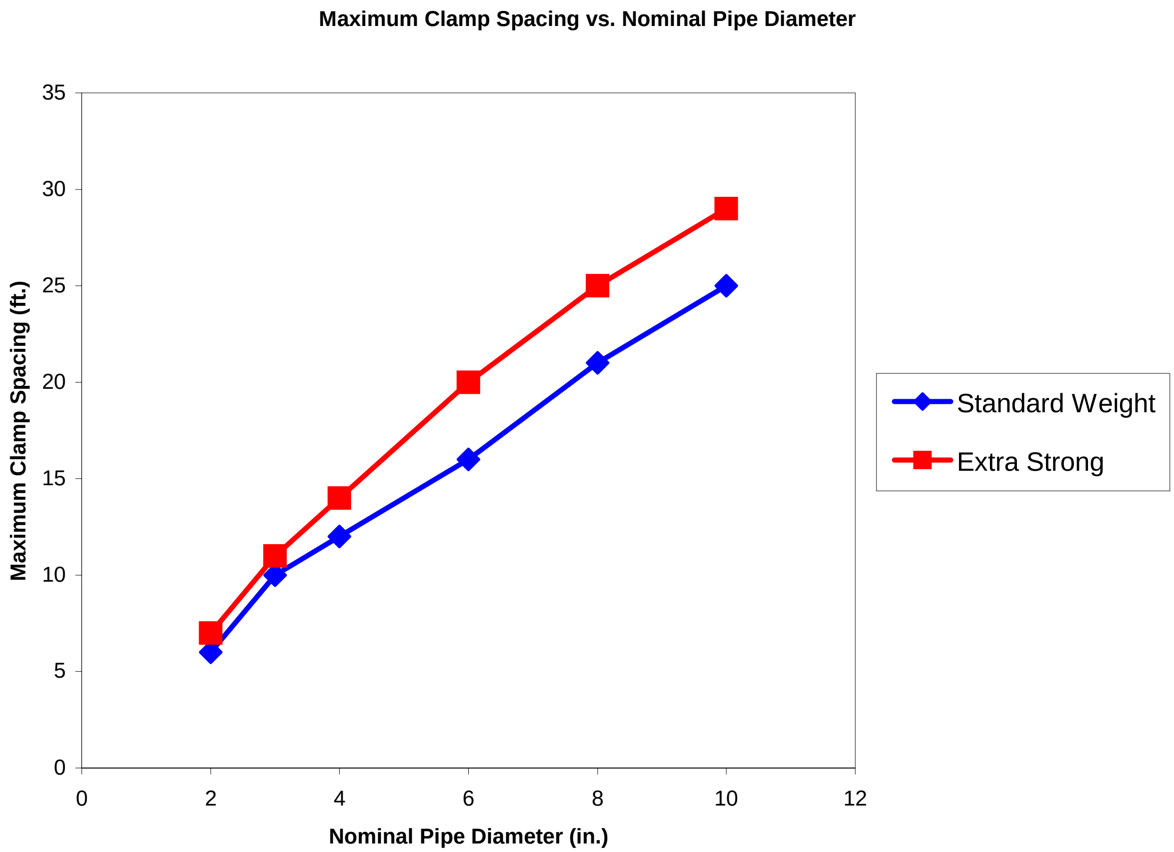


Figure 19. Comparison of Maximum Clamp Spacing for Standard and Extra-Strong Pipe

Evaluation of Results

Note that the maximum recommended clamp spacing for wave fatigue is longer than that for minimizing wave-induced VIV effects. If we remember that the wave water particle velocity is greatest at the splash zone, and decreases exponentially from the waters surface, it is prudent to use smaller clamp spacings near the splash zone and use larger spacings deeper, where the wave water particle velocity is much lower.

For a small diameter riser in 200 feet of water we would recommend the more conservative VIV-based spacing near the splash zone (say 2-3 clamps), and the wave force-based spacings below. Actually the clamp spacings could be larger than that shown for wave fatigue, because the velocities are much lower with water depths. The analysis tools provided here can assist in those calculations.

Also, please note that the much simpler to use MMS-recommended analysis yields results that are very similar to the more detailed analysis using the Stress-derived method.

Cathodic Protection Maintenance

Current day CP technology is much advanced from that in former years when these platforms were constructed, design should concentrate on retrofitting CP systems, if any, used previously. We have chosen not to cover this topic more fully in this report. The MMS advises us that maintenance is the number one issue. The scope of our work did not go into maintenance.

General Clamp and Bolting Design

Our understanding is that the design of the small-diameter clamping systems was not treated in much detail for these shallow water platforms. Many of the decisions on clamp design and installation were ad hoc. Clamping systems employed vary from simple U-bolt systems to more carefully designed clamp weldments. Nevertheless, there are some problems with clamps that need to be addressed.

The most competent clamp is one that maintains a spring load force on the riser so that the riser, excited by wave forces and VIV will not “rattle”, or vibrate in the clamp. Split clamps, see Figure 20 for an example, must be carefully designed (sized) to fit around the coated clamp in such a way that the spring loading of the clamp in bending, the coating viscoelasticity and the bolt tension spring action come to play in maintaining a solid grip on the riser over time. If the bolts are torqued until the clamp flanges meet, the length of the bolt in tension is small, and the spring is not soft enough. This condition is depicted on the left side of the clamp in the figure. If an old design is being fixed, a simple change is to add a “bolt tube” to one flange of the clamp so that the same torque on a bolt produces more spring action due to the increased length of bolt in tension. This change is shown on the right half of the clamp.

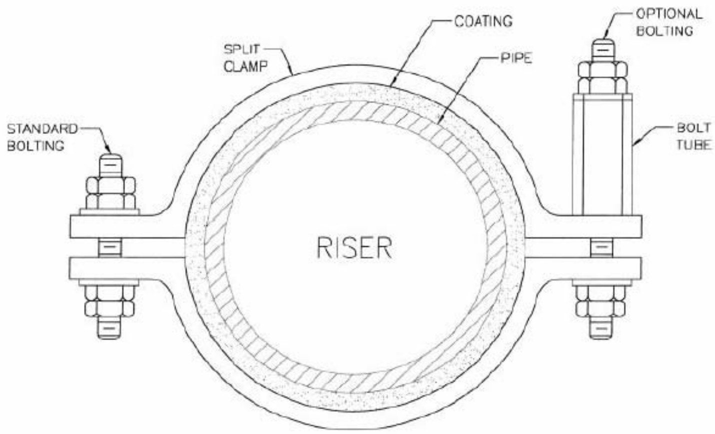


Figure 20(a). Typical Existing Clamp Modification.
(If new Installation is not feasible)

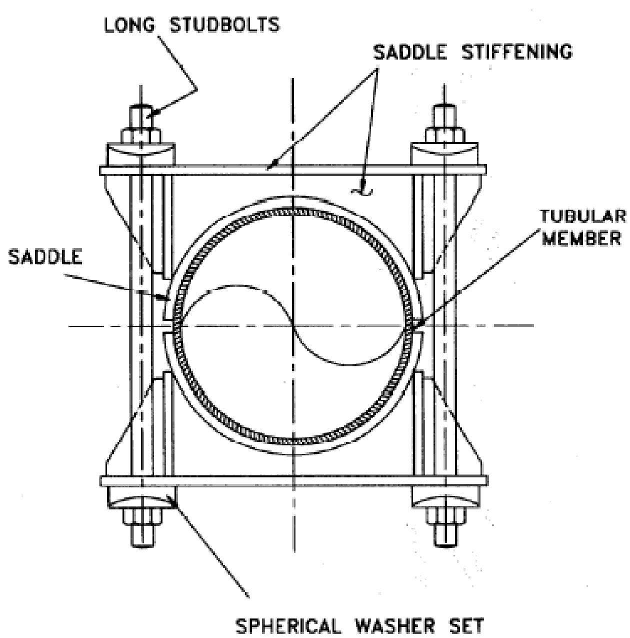


Figure 20(b). Typical Clamp For New Installation (from MMS).

If due to poor design or due to lack of torque, the riser can vibrate in the clamps due to oscillatory forces, then the resultant vibrations can cause the bolts to loosen. If the wrong type of bolts is used during ad hoc installation operations, the bolts can corrode and break away. Similarly if the clamp is not maintained, the clamp can corrode and break away.

The MMS provided us a calculation tool for riser clamp bolting, and this helpful spreadsheet based calculation tool is included in Appendix E.

The result of clamp failure – by any means – is to increase (usually double) the clamp spacing during operations from that intended in design. Of course, the riser is then less competent to resist the next hurricane that comes along, and it fails and/or leaks.

Clamps Near the Seafloor

Operators have reported that problems with the on-bottom stability of pipelines on the seafloor connecting to the riser have experienced failures. The issue is that these small-diameter lines are not subjected to a detailed stability design. Further if the on-bottom segments are buried or left to self-bury, the fact is that the on-bottom pipelines are being displaced in all directions by the shoaling hurricane waves by sediment transport or by mud flows (as has been prominent for large diameter pipelines due to Ivan). When the pipeline pulls away from the riser, clamped to the pipeline, either the lower clamp fails (which is good – to provide slack), or more likely the riser kinks at the clamp, resulting in a buckle and subsequent leaking. In the MMS database the failure due to on-bottom stability problems (root cause) is often reported as a riser failure (a secondary event).

There are two recommendations here: First, carefully design the on-bottom stability to resist major movements due to storms, and second, terminate clamping well above the seafloor so that the riser bend behaves like a steel catenary riser (SCR) segment, and thus the riser base can tolerate some reasonable movement of the on-bottom segment.

Riser/Clamp Remediation Alternatives

Operator/Owners have reported that the repair costs are the same whether the repairs are done just after a hurricane or in anticipation of a hurricane. We are told that these small-diameter risers are shut in prior to the evacuation for an approaching hurricane, depressurization of the risers, is not always done in the frenzy of preparing the platform to shut in.

We are further told (see above operator feedback) that it is difficult to determine what risers are at risk of failing prior to a hurricane. Prominent marine growth makes inspection difficult, and scraping off the growth might damage coatings. These comments have merit. Note: We understand from the MMS that there is at least one system to remove marine growth without damaging the coatings.

It would appear to be prudent for operator/owners to use their specific riser damage experience in recent storms to guide their strategy in remediation of the remaining riser/clamp systems that have not yet failed. If clamps are the problem, it is possible to design an add-on “over-clamp” that divers can place on in addition to the existing clamps to afford a secondary support if the primary clamp fails. The clamps of greatest concern are those near the splash zone, readily accessible by divers.

If failures have occurred at the riser base, as discussed previously, one might want to make the riser base more free-hanging by removing a bottom clamp.

REFERENCES

1. Mandke, J. S., et al, Evaluation of *Hurricane-Induced Damage to Offshore Pipelines*, OCS Report MMS 95-0044, Contract Number 14-35-0001-30748 to Southwest Research Institute, March 1995.

2. Daniels. G. R., *Hurricane Andrew's Impact on Natural Gas and Oil Facilities on the Outer Continental Shelf*, Interim MMS 94-0031 Report as of November 1993.

3. American Petroleum Institute, *API RP 1111: Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines*, July 1999.

4. Det Norske Veritas, Offshore Standard OS-F101: Submarine Pipeline Systems, January 2000.

5. API RP 2A-WSD.

6. Communications with Sean Verret and Elizabeth Komiskey, MMS.

7. 1984 DOE Curve.

APPENDIX A

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
23	Conventional Riser	Wet Buckle, caused by waves and/or current	Riser clamp failure - Installation	9	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Installation Quality Plan, Installation Procedures, Installation Records, post installation inspection (post clamps and post risers), periodic visual inspections.	90
24	Conventional Riser	Rupture	Fatigue: Vortex Induced Vibration	9	Loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Accurate Natural Frequency Prediction for waves and current, periodic inspections, periodic visual inspections.	90
25	Conventional Riser	Rupture	Riser Base Pulled Away, due to mudslide	9	Loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Ensure riser have as much room as possible to absorb mudslide, install non-return valve(s) to minimize pollution, flush riser prior to production stop, when storm conditions are predicted.	90
15	Conventional Riser	Wet Buckle	Vessel Collision	8	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Prevent Cargo load/unload in riser vicinities, position riser bay downstream of prevailing current and wind, consider maintaining an emergency tug in general area	80

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
8	Conventional Riser	Dry Buckle	Wave and Current: Clamp(s) open due to vibration, bolts and nuts vibrated loose	10	Collapse of a section of Riser	7	Design: Vibration to be accounted for in design. Periodic visual inspections.	70
16	Conventional Riser	Wet Buckle	Floating Object Impact	7	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design. This is not currently part of any recommended practice or rule (?), consider determining typical impact load and incorporate to RP's and/or rules.	70
18	Conventional Riser	Wet Buckle	Wave and Current: Clamps open due to vibration, bolts and nuts vibrated loose	7	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Vibration to be accounted for in design, periodic visual inspections.	70
19	Conventional Riser	Wet Buckle	Wave and current, clamp(s) broken due to corrosion	7	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Ensure clamps corrosion protection (cathodic protection+corrosion coating), periodic visual inspections.	70

FMECA Report

Date: 28-Apr-2005

Rev: 0

Equipment: Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order

Phase: Operation

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
21	Conventional Riser	Wet Buckle, caused by waves and/or current	Riser clamp failure - Design	7	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Ensure accurate design basis, wind and current loads, structural analysis for clamp, corrosion protection design, specially when clamps are not welded to jacket, design for installation simplicity. Design shall take riser and clamp polymeric or elastomeric coating creep into account (consider using BELLEVILLE or SCHNORR whasher springs), material compatibility, consider qualification testing, periodic visual inspections.	70
5	Conventional Riser	Dry Buckle	Vessel Collision	8	Collapse of a section of Riser	8	Prevent Cargo load/unload in riser vicinities, position riser bay downstream of prevailing current and wind, consider maintaining an emergency tug in general area	64

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
1	Conventional Riser	Dent	Dropped Object	9	Prevent pigging, restricted flow, erosion, stress concentration, corrosion due to external coating breakdown	7	Design: Prevent cargo load/unload in riser vicinities, pre-install riser inside jacket frame, design cranes opposite to riser bay	63
2	Conventional Riser	Dent	Vessel Collision	9	Prevent pigging, restricted flow, erosion, stress concentration, corrosion due to external coating breakdown	7	Prevent Cargo load/unload in riser vicinities, position riser bay downstream of prevailing current and wind, consider maintaining an emergency tug in general area	63
13	Conventional Riser	Dry Buckle, caused by waves and/or current	Riser clamp failure - Installation	9	Collapse of a section of Riser	7	Installation Quality Plan, Installation Procedures, Installation Records, post installation inspection (post clamps and post risers), periodic visual inspections.	63
17	Conventional Riser	Wet Buckle	Wave and Current: Incorrect clamp spacing	6	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design Basis, May need to upgrade 100 year wave and current loads;Design Criteria: May need to increase RP's and rules safety factors	60
7	Conventional Riser	Dry Buckle	Wave and Current: Incorrect clamp spacing	8	Collapse of a section of Riser	7	Design Basis, May need to upgrade 100 year wave and current loads;Design Criteria: May need to increase RP's and rules safety factors	56

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
11	Conventional Riser	Dry Buckle, caused by waves and/or current	Riser clamp failure - Design	8	Collapse of a section of Riser	7	Ensure accurate design basis, wind and current loads, structural analysis for clamp, corrosion protection design, specially when clamps are not welded to jacket, design for installation simplicity. Design shall take riser and clamp polymeric or elastomeric coating creep into account (consider using BELLEVILLE or SCHNORR whasher springs), material compatibility, consider qualification testing, periodic visual inspections.	56
14	Conventional Riser	Wet Buckle	Dropped Object	5	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Prevent cargo load/unload in riser vicinities, pre-install riser inside jacket frame, design cranes opposite to riser bay	50

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
22	Conventional Riser	Wet Buckle, caused by waves and/or current	Riser clamp failure - Fabrication	5	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Quality plan, welding qualification process, dimensional control, proper shipping/receiving and storage procedures, periodic visual inspections.	50
27	Conventional Riser	Rupture	Clamp Spacing too wide, causing the riser to constantly impact the clamp. May be caused by improper initial design, creep of the clamp liner, creek of the riser coating (case of splash zone coating e.g. splashtron), improper installation (diver did not tighten bolts properly).	5	Loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Ensure design incorporates proper corrosion protection (cathodic protection and corrosion coating), periodic intelligent pigging, visual inspection.	50
9	Conventional Riser	Dry Buckle	Wave and current, clamp(s) broken due to corrosion	7	Collapse of a section of Riser	7	Design: Ensure clamps corrosion protection (cathodic protection+corrosion coating), periodic visual inspections.	49
3	Conventional Riser	Dent	Floating Object Impact	7	Prevent pigging, restricted flow, erosion, stress concentration, corrosion due to external coating breakdown	6	Design. This is not currently part of any recommended practice or rule (?), consider determining typical impact load and incorporate to RP's and/or rules.	42

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: **28-Apr-2005**	**Phase:**	**Operation**
Rev: **0**		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
4	Conventional Riser	Dry Buckle	Dropped Object	6	Collapse of a section of Riser	7	Design: Prevent cargo load/unload in riser vicinities, pre-install riser inside jacket frame, design cranes opposite to riser bay	42
6	Conventional Riser	Dry Buckle	Floating Object Impact	6	Collapse of a section of Riser	7	Design. This is not currently part of any recommended practice or rule (?), consider determining typical impact load and incorporate to RP's and/or rules.	42
28	Conventional Riser	Puncture	Dropped Object	4	Loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Prevent cargo load/unload in riser vicinities, pre-install riser inside jacket frame, design cranes opposite to riser bay	40
12	Conventional Riser	Dry Buckle, caused by waves and/or current	Riser clamp failure - Fabrication	5	Collapse of a section of Riser	7	Quality plan, welding qualification process, dimensional control, proper shipping/receiving and storage procedures, periodic visual inspections.	35

FMECA Report	**Equipment:**	**Hurricane Lili FMECA - Conventional Riser* Damage Risks - RPI Descending Order**
Date: 28-Apr-2005	**Phase:**	**Operation**
Rev: 0		

Index	Component Identification	Potential Failure Mode(s)	Potential Cause(s) of Failure	Probability Index	Potential Effect(s) of Failure	Severity Index	Current Design Controls	Risk Priority Index
20	Conventional Riser	Wet Buckle	Thermal Buckling	3	Collapse of a section of Riser, loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design:Flowline expansion loops, Flowline sleds with sliding connections, design lower riser section with sufficient room for thermal expansion.	30
26	Conventional Riser	Rupture	Corrosion	3	Loss of product to the environment, flooded riser, fire hazard, if gas/multiphase, potential hazard to vessels (loss of flotation).	10	Design: Ensure design incorporates proper corrosion protection (cathodic protection and corrosion coating), periodic intelligent pigging.	30
10	Conventional Riser	Dry Buckle	Thermal Buckling	3	Collapse of a section of Riser	7	Design:Flowline expansion loops, Flowline sleds with sliding connections, design lower riser section with sufficient room for thermal expansion.	21

FMEA Criticality Analysis Index Codes

Severity Index

Severity	Criteria	Ranking
Hazardous	Hazardous effect. Safety related. Sudden failure. Noncompliance with government regulations.	10
Serious	Potential hazardous effect. Able to stop product/service without mishap. Safety related. Time-dependent failure. Disruption to subsequent process operations. Compliance with government regulation is in jeopardy.	9
Extreme	Customer very dissatisfied. Extreme effect on process/service; equipment damaged. Product/service incomplete but safe.	8
Major	Customer dissatisfied. Major effect on service; rework on service necessary. Product/service performance severely affected but functionable and safe.	7
Significant	Customer experiences discomfort. Product/process performance degraded, but operable and safe.	6
Moderate	Customer experiences some dissatisfaction. Moderate effect on product or service performance.	5
Minor	Customer experiences minor nuisance. Minor effect on product or service performance. Fault does not require attention.	4
Slight	Customer slightly annoyed. Slight effect on product or service performance.	3
Very slight	Customer more likely will not notice the failure. Very slight effect on product / process performance.	2
No	No discernible effect on product or subsequent processes.	1

FMEA Criticality Analysis Index Codes

Occurrence Index

Occurrence	Criteria	Ranking
Almost Certain	Failure almost certain.	10
Very High	Very high number of failures likely.	9
High	High number of failures likely.	8
Moderately High	Frequent high number of failures likely.	7
Medium	Moderate number of failures likely.	6
Occasional	Occasional number of failures likely.	5
Slight	Few failures likely.	4
Very slight	Very few failures likely.	3
Rare	Rare number of failures likely.	2
Unlikely	Failure unlikely. History shows no failures.	1

This Spreadsheet is to be used in FMEAC analysis.

Preliminary work:

Before any work is done on a project, the project team needs to establish the tolerance level for risk.

The ranking system yields a number called the "risk priority index" (RPI). This is the result of the multiplication of the Probability Index x Severity Index x Detection Index.

Since each of the indexes ranges from 1 to 10, the best RPI would be 1 and the worst 1000. Common sense needs to be used for the RPI. The upper limit for acceptability is currently set to an item which has a moderate number of failures (index =6), a major severity (severity index = 7), and a low likelihood of being detected (detection index = 6). The highest acceptable RPI is 6 x 6 x 7=252.

Items under analysis which score above 252 need to be re-engineered for mitigation measures until they fall within acceptable limits.

Ranking

A specialist will input the failure modes he or she finds even remotely possible, and then the sheet will be presented to a group of team members, which will rank each failure mode according to a group-agreed subjective ranking (see the "Index" tab) for :

- *Probability of a failure event to occur*
- *If a failure occurs, how severe are the consequences*

The group should also evaluate the "Current Design Controls" column. This is meant to identify the means to prevent the failure. Examples are as follows:

- **Design**: Proper design would size the component for strength, fatigue loads, impact loads, corrosion, etc. The design also involves material selection, electrical isolation, thermal insulation, corrosion coating, cathodic protection, etc.
- **Procedural**: Sometimes a failure can be prevented through proper handling procedures, installation procedures, quality plans, check lists, etc.
- **Informational**: Tags, warnings, published charts and drawings, personnel training and indoctrination may help preventing a failure
- **Testing and qualification testing**: Testing components to simulate how they will work in real time: Interfaces, fit testing, factory acceptance tests, etc.
- **Fabrication and manufacturing standards**: Following industry standards may help prevent failures.
- **Redundancies**: Redundant design may impose several barriers to failure, so if a single component system fails there are still other components or systems in place that may prevent

Graphs, how they are built and what they mean:

The graphs show the overall range, the acceptable range and the actual range, after completion of the ranking process by the review team.

The graphs of interest are the ones which highlight the actual range. The ordinates is the RPI, and the abcissas is the GAUSS distribution function, where σ is the Standard Deviation, μ is the Mean, e = 2.71828..., and Π = 3.14159... .

$$\boxed{Y = \frac{1}{\sigma\sqrt{2\pi}} e^{1/2(X-\mu)^2/\sigma^2}}$$

APPENDIX C

APPENDIX C.

Calculation Methodology for Clamp Spacing Determination

Stress Engineering Contributors:

Stuart Harbart
Randy Long, P.E.
Chad Searcy

Input Data for Clamp Spacing Solution

Material Data

E, Msi	29
S_y, ksi	42
S_u, ksi	76
ν	0.3

Pipe Data

OD, inch	10.75
Nominal Wall Thickness, inch	0.5
D/t	21.50
Cross-section Area, in^2	16.10

Pressure Data

Design Operating Pressure, psi	1,480
Hydrotest Multiplier	1.5
Hydrotest Pressure, psi	2,220.00
Water Depth to Top Termination, ft	0
External Pressure @ Top Termination, psi	0.00
Water Depth to Seafloor, ft	200
External Pressure @ Seafloor, psi	88.88

API RP 1111 Pipe Design Calculations

Seafloor Design Considerations

Design Against Burst

Burst Pressure, P_b	$0.9(S_y + S_u)(t/D\text{-}t))$	5,180.49
Burst Pressure, P_b	$0.45(S_y + S_u)\ln(D/D_i)$	5,184.60
Factor of Safety Against Burst	P_b/P_d	**3.50**
Recommended Factor of Safety	--	1.67
Utilization Factor	--	0.48
Factor of Safety Against Hydrotest	P_b/P_h	**2.33**

Recommended Factor of Safety	--	1.33
Utilization Factor	--	0.57

Design Against Collapse

Elastic Collapse Pressure, Pe	$2E(t/D)^3 / (1-\nu^2)$	6,413.15
Yield Pressure @ Collapse, Py	$2S_y(t/D)$	3,906.98
Collapse Pressure, Pc	$P_yP_e/(P_y^2 + P_c^2)^{1/2}$	3,336.57
Factor of Safety Against Collapse	P_c/P_o	**37.54**
Recommended Factor of Safety	--	1.43
Utilization Factor	--	0.04

Design Against Buckle Propagation

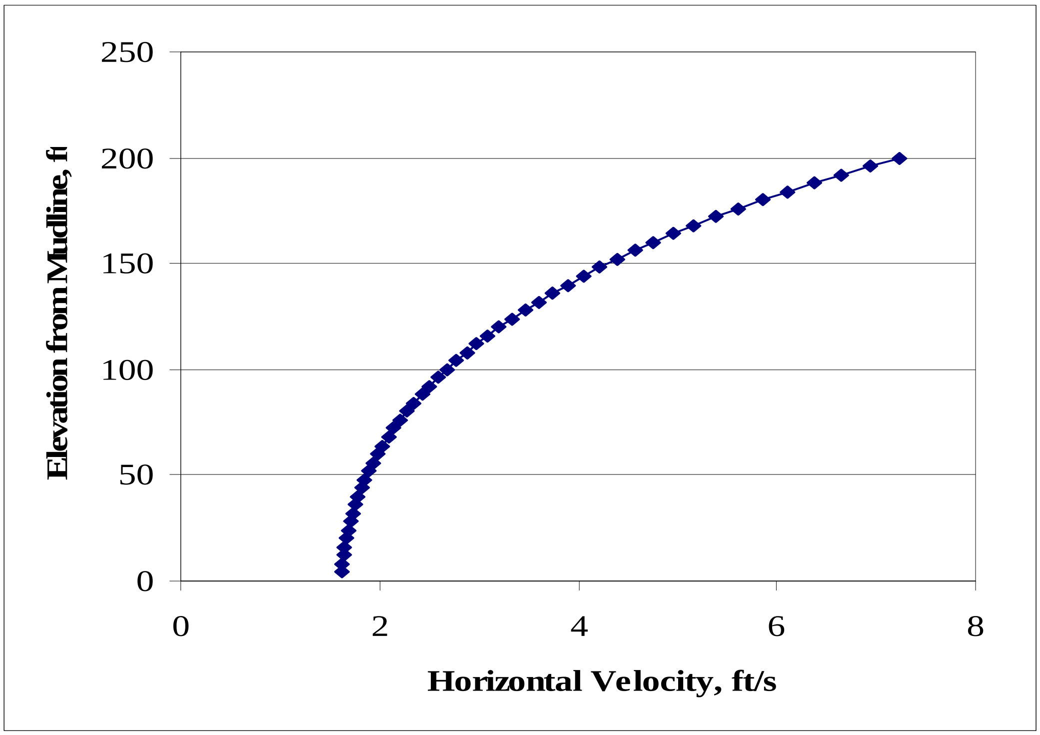
Buckle Propagation Pressure, Pp	$24S_y(t/D)^{2.4}$	639.16
Factor of Safety Against Buckle Propagation	P_p/P_o	**7.19**
Recommended Factor of Safety	--	1.25
Utilization Factor	--	0.17

Stokes Fifth Order Wave Calculation

Water depth, d, ft	200	keep less than 2900-ft		
Wave Period, Tp, sec	10.7	solve stoke's 5th		
Wave Height, ft	24.18			
Θ	0			
g	32.174		A_{11}	0.23335782
λ	**0.129646**		A_{13}	-0.163840737
k	**0.010808**		A_{15}	-0.218781529
kd	2.1616736		A_{22}	0.001112041
tanh(kd)	0.973835933		A_{24}	0.014843933
C	4.40039686		A_{33}	-3.79513E-05
S	4.285264581		A_{35}	0.000186347
B33	0.439667105		A_{44}	8.1359E-07
B35	1.458782655		A_{55}	8.83669E-10
B55a	0.428270549		λ_1	0.029888863
B55b	6.22077E-09		λ_2	2.28848E-05
B55	0.428270555		λ_3	-7.58744E-08
			λ_4	2.29848E-10
C1	1.057791994		λ_5	3.23657E-14
C2	1.556013689			
Eqn. 3.89	24.18			
Constraint	-1.23546E-10			
co^2	2898.883341	p. 59		
c	54.32953358	p. 59, Eqn. 3.90		
L=cT	581.3260093			
$L=2\pi/k$	581.3260092			

858.324095	shallow
570.9243152	deep
581.3260092	

Typical Plot of Maximum Velocity Calculations (Stokes Fifth)



Simple Beam Calculation – Pinned Ends

Pinned Solution

OD, inch	10.75	
Wt, inch	0.5	
ID, inch	9.75	
E, psi	2.90E+07	
Depth	200	
s1, ft	91	Lowest Clamp Position
s2, ft	200	Highest Clamp Position

rho_sw	1.99
Cd	1.2

Max Stress	**9.5309**	**ksi**

Calculation of Predicted Fatigue Life of Riser

CALCULATION OF PREDICTED FATIGUE LIFE FOR WELDED AND UN-WELDED REGIONS

Input in Yellow Areas

19.1	**Bending Stress (ksi) Range from Analysis (Range = two times amplitude)**
3.0	**Stress Concentration Factor for Connector or other Unwelded Metal**
1.0	**Stress Concentration Factor for Weld Region**
10.7	**Zero Upcrossing Period, Tz, seconds**
10438	**No. of Cycles to Failure for Unwelded Metal (INCLUDES SAFETY FACTOR OF 2)**
17607	**No. of Cycles to Failure for Weld Region (INCLUDES SAFETY FACTOR OF 2)**
1.29	**Life to Failure of Unwelded Metal, Days**
2.18	**Life to Failure of Weld Region, Days**

Design Fatigue Curves Used:

Used For:	**Unwelded Metal**	**Weld Region**	
Name of Curve	1984 DOE B	1984 DOE W	
For Service in:	Salt Water	Salt Water	
SaltWater Factor	2	2	(1984 Code suggests a reduction in life of 2 for saltwater exposure)
Slope of Curve, m	4	3	
Curve Constant, A	4.465E+11	4.88E+08	

N=Number of Cycles to Failure = A * (Stress)$^{-m}$ where Stress is in ksi

3.0	**Storm Duration, hours**
1009.3	**No. of Cycles during Given Storm**
9.67%	**% of Overall Fatigue Life used During Single Storm (Unwelded Material)**
5.73%	**% of Overall Fatigue Life used During Single Storm (Welded Material)**

Notes Concerning Fatigue Calculations

- Task: What cyclic stress range will result in a long-life riser?

- For fatigue curves, Stress chose:

    1. 1984 DOE B for Unwelded Base Metal.
       This was the only reasonable choice

    2. 1984 DOE W for Welded Regions
       This curve was chosen because it is conservative.
       It predicts low cycle fatigue.
       It is associated with one-sided fillet welds.
       Another choice would be the F2 curve, which is used
       for flange welds

- The Calculator Requires:

    1. Bending Stress Range (ksi) which is taken from Analysis
       (Bending/VIV)

    2. SCF for the Unwelded Material.
       A value of 3.0 was chosen.
       The base metal SCF is definitely greater than 1.0 but less than 10.

    3. SCF for Welded Region.
       A value of 1.0 was chosen.
       Since we are already assuming a lousy weld, an SCF is not
       needed.

    4. Assumed cycle rate for the storm (seconds)

- The Calculator Determines:

    1. Number of cycles to failure of Unwelded Material.

    2. Number of Cycles of Failure of the Welded Material.

    3. Life to Failure of the Unwelded Material (days).

    4. Life to Failure of the Welded Material (days).

  The number of cycles to failure is reduced by a Saltwater Service Factor
  of 2.0. This is based on the recommendation from the 1984 DOE Code.

- Life to Failure should be compared to:

    1. Storm Duration

    2. Frequency of storm occurrences

Large Bending Stress Ranges may be acceptable when designing for large but infrequent storms.

APPENDIX D

Appendix D

Details for Clamp Spacing Calculations

Task: Calculate Maximum Clamp Spacing for 2-inch through 10-inch Risers.

Table

A. Pipe Properties and Dimensions

AISI 1040 HR: E = 29 Msi; Yield Strength = 42 ksi; Ultimate Strength = 76 ksi

Standard Weight

Nominal Diameter (in.)	Outer Diameter (in.)	Thickness (in.)	Weight (lbf/ft)
2	2.375	0.154	3.65
3	3.500	0.216	7.58
4	4.500	0.237	10.79
6	6.625	0.280	18.97
8	8.625	0.322	28.55
10	10.750	0.365	40.48

Extra Strong

Nominal Diameter (in.)	Outer Diameter (in.)	Thickness (in.)	Weight (lbf/ft)
2	2.375	0.218	5.02
3	3.500	0.300	10.25
4	4.500	0.337	14.98
6	6.625	0.432	28.57
8	8.625	0.500	43.39
10	10.750	0.500	54.74

Table, Continued

Outer Diameter (in.)	Class	Rating (psig)
2.375	900 (PN 150)	2220
3.500	900 (PN 150)	2220
4.500	900 (PN 150)	2220
6.625	900 (PN 150)	2220
8.625	600 (PN 100)	1480
10.750	600 (PN 100)	1480

Outer Diameter (in.)	Class	Rating (psig)
2.375	1500 (PN 250)	3705
3.500	1500 (PN 250)	3705
4.500	1500 (PN 250)	3705
6.625	1500 (PN 250)	3705
8.625	900 (PN 150)	2220
	900 (PN 150)	2220

Calculation Details:

B. Maximum Allowable Clamp Spacing vs. Pipe Diameter

AISI 1040 HR: E = 29 Msi; Yield Strength = 42 ksi; Ultimate Strength = 76 ksi
100-Year Hurricane: Wave Height = 65.5 ft; Wave Period = 12.6 s; Coefficient of Drag = 1.2

Standard Weight

Nominal Diameter (in.)	Maximum Clamp Spacing (ft)	Bending Stress Range (ksi)	Cycles to Failure - Unwelded Material	Cycles to Failure - Welded Region
2	6	15.0	27,002	35,914
3	10	19.4	9,776	16,763
4	12	18.9	10,714	17,955
6	16	18.2	12,634	20,318
8	21	19.8	8,927	15,659
10	25	19.1	10,375	17,528

Extra Strong

Nominal Diameter (in.)	Maximum Clamp Spacing (ft)	Bending Stress Range (ksi)	Cycles to Failure - Unwelded Material	Cycles to Failure - Welded Region
2	7	15.6	23,467	32,327
3	11	18.0	13,067	20,838
4	14	19.1	10,367	17,518
6	20	19.1	10,276	17,402
8	25	18.7	11,307	18,695
10	29	18.9	10,795	18,057

Table Continued

Nominal Diameter (in.)	Maximum Clamp Spacing (ft)	Life to Failure - Unwelded Material (days)	Life to Failure - Welded Region (days)
2	6	3.94	5.24
3	10	1.43	2.44
4	12	1.56	2.62
6	16	1.84	2.96
8	21	1.30	2.28
10	25	1.51	2.56

Extra Strong

Nominal Diameter (in.)	Maximum Clamp Spacing (ft)	Life to Failure - Unwelded Material (days)	Life to Failure - Welded Region (days)
2	7	3.42	4.71
3	11	1.91	3.04
4	14	1.51	2.55
6	20	1.50	2.54
8	25	1.65	2.73
10	29	1.57	2.63

Calculation of Clamp Spacing Required to Maintain Riser in First Mode VIV:

Table:

Umax	17.38

C. Fundamental Frequency of Clamped Riser Pipe

AISI 1040 HR: E = 29 Msi; Yield Strength = 42 ksi;
Ultimate Strength = 76 ksi
100-Year Hurricane: Wave Height = 65.5 ft;
Wave Period = 12.6 s; Umax = 17.38 ft/s

Standard Weight

Nominal Diameter (in.)	Max. Clamp Spacing based on Wave Fatigue (ft)	First Modal Frequency - FMF (rad/s)
2	6	47.44
3	10	25.23
4	12	22.73
6	16	19.02
8	21	14.45
10	25	12.75

Extra Strong

Nominal Diameter (in.)	Max. Clamp Spacing based on Wave Fatigue (ft)	First Modal Frequency - FMF (rad/s)
2	7	33.93
3	11	20.37
4	14	16.34
6	20	11.90
8	25	9.99
10	29	9.35

Table, Continued

Nominal Diameter (in.)	Strouhal Maximum Shedding Frequency - SMF (rad/s)	Max. Clamp Spacing if FMF = SMF (ft)	Check First Modal Frequency - FMF (rad/s)
2	110.35	3.93	110.35
3	74.88	5.80	74.88
4	58.24	7.50	58.24
6	39.56	11.10	39.56
8	30.39	14.48	30.39
10	24.38	18.08	24.38

Extra Strong

Nominal Diameter (in.)	Strouhal Maximum Shedding Frequency - SMF (rad/s)	Max. Clamp Spacing if FMF = SMF (ft)	First Modal Frequency - FMF (rad/s)
2	110.35	3.88	110.35
3	74.88	5.74	74.88
4	58.24	7.42	58.24
6	39.56	10.97	39.56
8	30.39	14.33	30.39
10	24.38	17.96	24.38

APPENDIX E

Turn of the Nut Method

for A325 and A490 Bolts

Bolt Information

Bolt Type	A325		
Bolt Diameter	1	in	
Youngs Modulus	29000	ksi	
Threads per Inch	8		per Thread Table AISC ASD 9th Ed. Pg 4-147
Tensile Bolt Area	0.606	in^2	
Pitch	1/8		

Bolt Load

Min Pre-Tension	51	kips	per Table J3.7 AISC ASD 9th Ed

Rotation for Fully Tensioned Bolts

Rotation Pass			
Snug Tight	1/3		see Turn of the Nut Factors Tab
Length of Travel	0.041625	in	

Length of Bolt in Tension

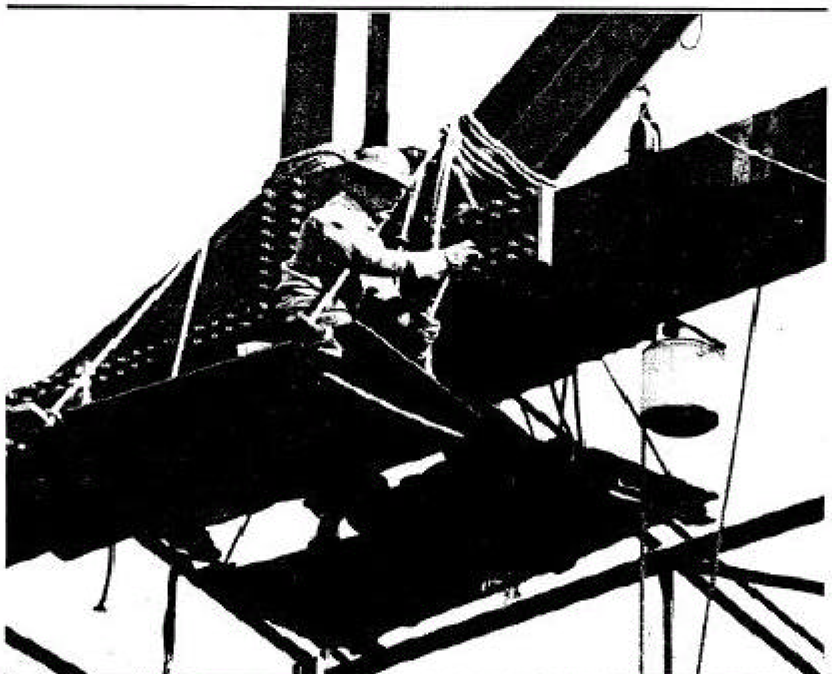
	14.33746	in

U.S. Department of Transportation
Federal Highway Administration

High-Strength Bolts for Bridges

Office of Technology Applications

Engineering Applications Division



Demonstration Project No. 88

Report No. FHWA-SA-91-031

May 1991

TABLE 11.5A - REQUIRED FASTENER TENSION (Kips)

Bolt Dia. (in)	1/2	5/8	3/4	7/8	1	1 1/8	1 1/4	1 3/8	1 1/2
M164 (A325)	12	19	28	39	51	56	71	85	103
M253 (A490)	15	24	35	49	64	80	102	121	148

2.4 Following snug tightening, mark nut or drive socket to a reference point on bolt tension calibrator and further tighten to the rotation shown below.

Bolt Length	4 x bolt dia. or less	Greater Than 4 but no more than 8x bolt dia.	Greater than8 x bolt dia.
Required Rotation	1/3	1/2	2/3

2.5 At this rotation, the minimum bolt tension shall be as follows:

Bolt Dia. (in)	1/2	5/8	3/4	7/8	1	1 1/8	1 1/4	1 3/8	1 1/2
M164 (A325)	13	20	29	41	54	59	75	89	108
M253 (A490)	16	25	37	51	67	84	107	127	155

U.S. Department of the Interior

Non-Grouted Mechanical Clamps
for Structural Applications

MMS

Engr: S M Verret
Date: 28-Apr-05

Clamped Member Information

Diameter of Tubular Member (see Sketch 1)	D	20	in
Wall Thickness of Tubular Member	T	0.5	in
Youngs Modulus of Cord Steel	E_s	29000	ksi
	D/T	40	Ratio of D/T is OK

Clamp Information

Clamp Length (see Sketch 1)	L	21	in
Surface Area	A_s	1319.469	in^2
	L/D	1.05	Ratio of L/D is OK

Bolt Information

Bolt Type		A325	Select Bolt Type	
Number of Bolts	n	8		
Bolt Diameter (see Sketch 2)	D_b	1	in	
Threads per Inch		8		per Thread Table AISC ASD 9th Ed. Pg 4-147
Youngs Modulus of Studbolt	E_b	29000	ksi	
Stressed Length of Studbolt (see sketch 2)	L_b	12	in	
Min Pre-Tension	T_b	51	kips	per Table J3.7 AISC ASD 9th Ed
Tensile Stress Area of Studbolt	A_b	0.605745	in^2	
Bolt Stiffness Parameter	K_b	0.009615	Kb is OK	

Constants and Factors

Factor of Safety	G_f	1.7	(Constants and Factors Tab)
Surface Condition Factor	C_s'	0.85	(Constants and Factors Tab)

Studbolt Load in Connection

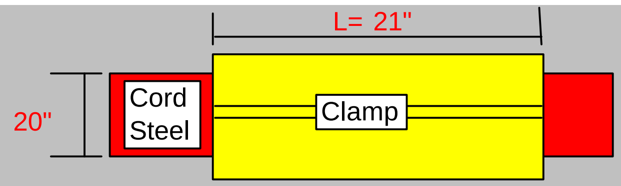
Total Pre-Tension Load in Connection	F_n	408	kips

Slip Strength

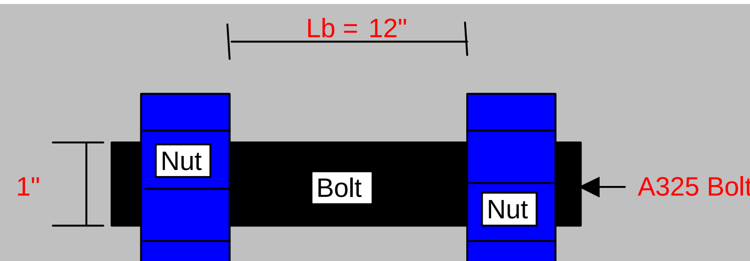
Slip Stength Stress	u_c	0.14291	ksi

Allowable Force before Slip Occurs

	F	188.5652	kips



Sketch 1



Sketch 2